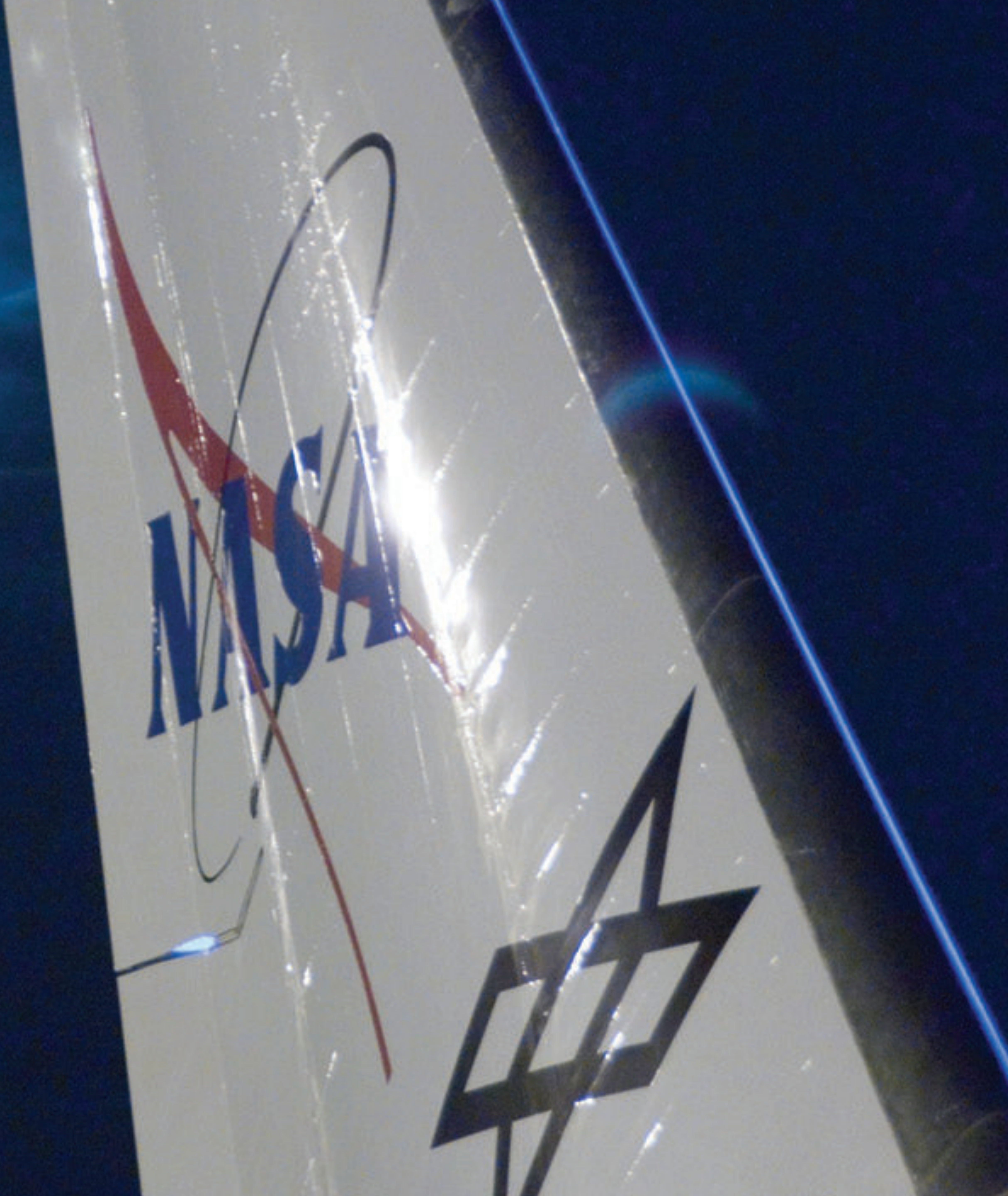
Cold, Small, and Plentiful

The Future of Instrumentation for Far-IR Astrophysics

SOFIA Tele-Talk

August 23rd, 2023



Michael Zemcov

RIT

Rochester Institute of Technology

It Takes a Village

With Thanks To…

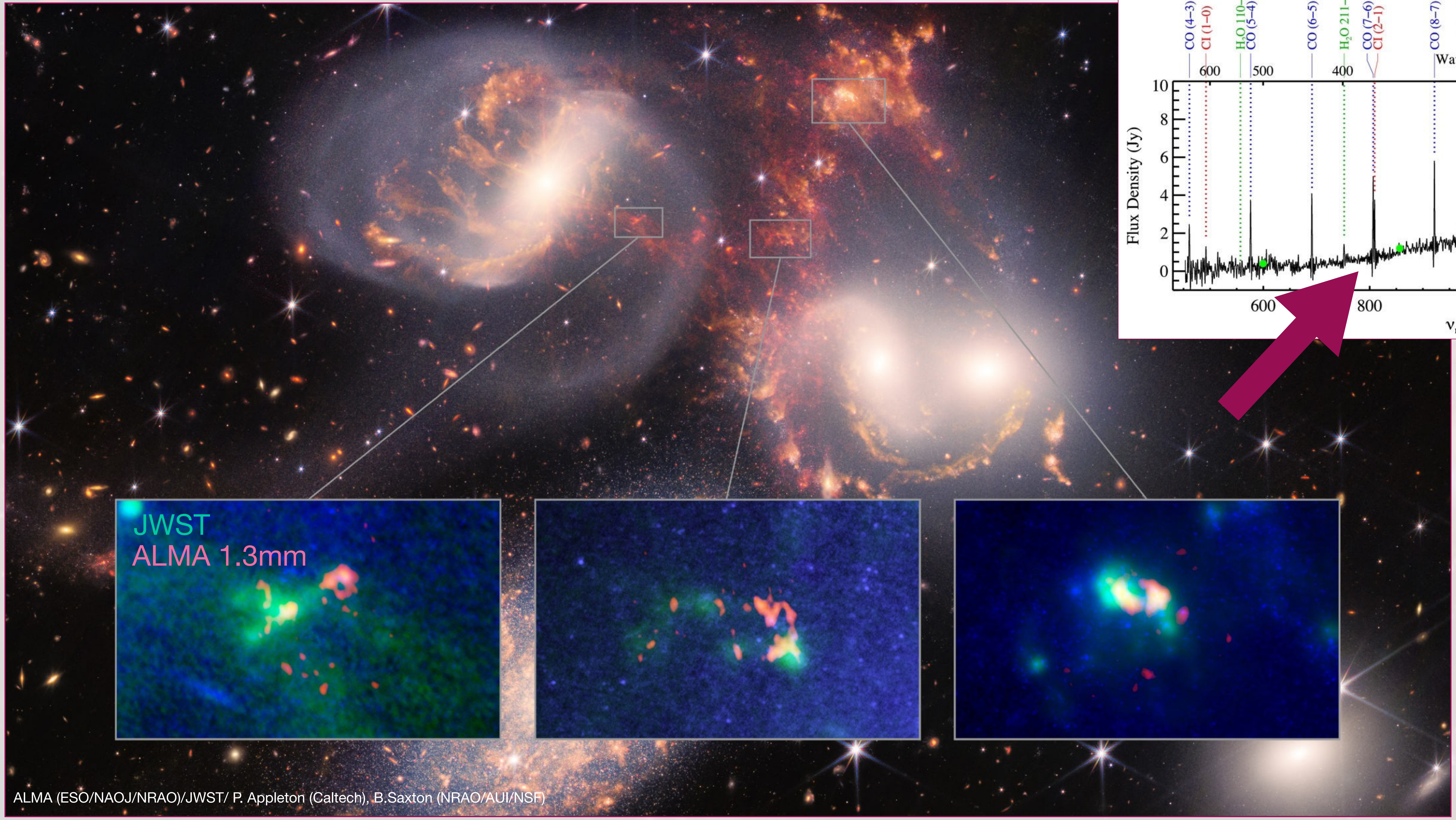
Matt Bradford (JPL)
Jake Connors (NIST)
Jeff Filippini (U. Illinois)
Reinier Janssen (JPL)
Phil Mauskopf (ASU)
Gary Melnick (Harvard)
Roger O'Brient (JPL)

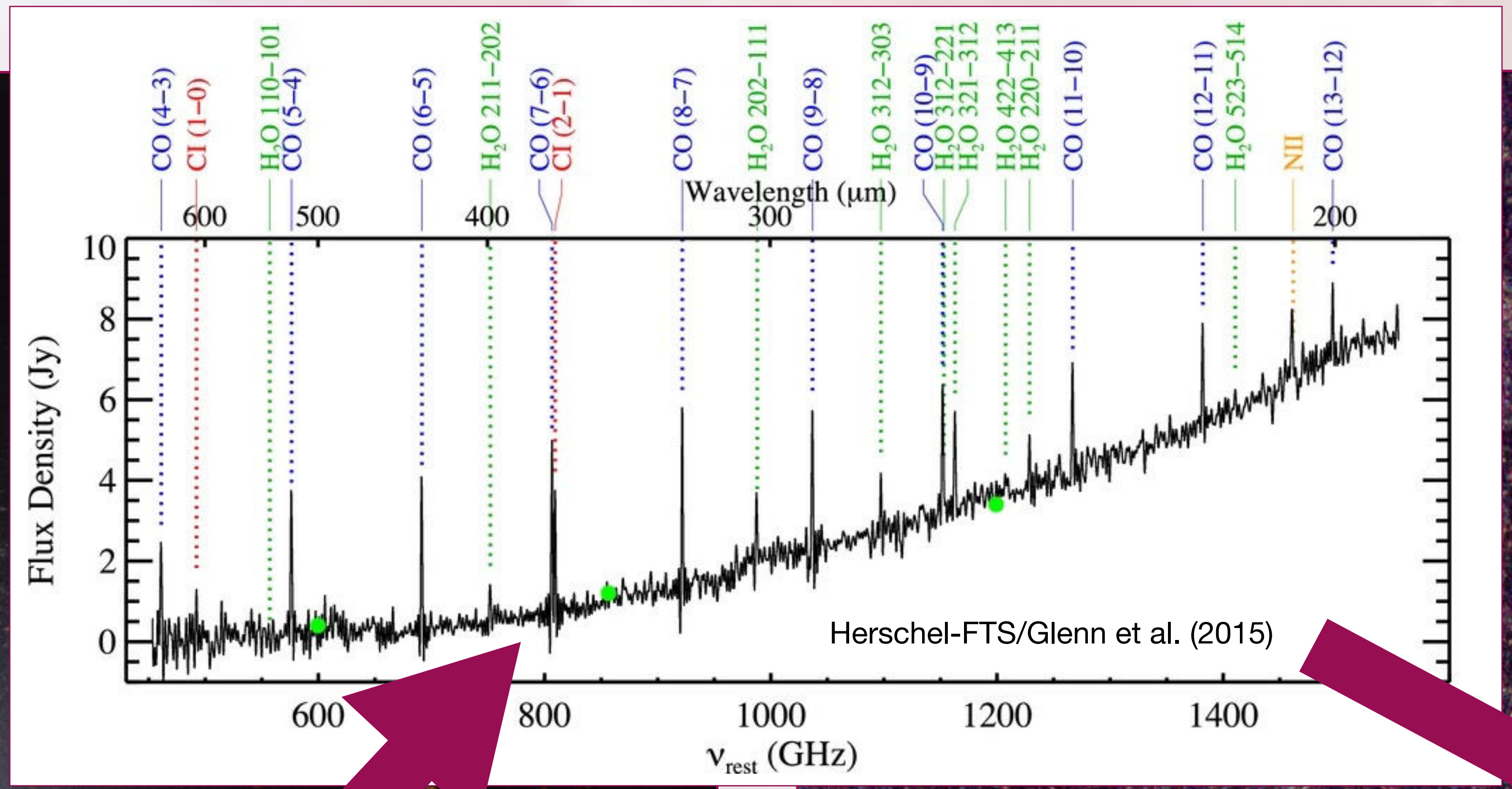
Jorge Pineda (JPL)
Karwan Rostem (Goddard)
Bernhard Schulz (DSI)
Locke Spencer (U. Alberta)
Gordon Stacey (Cornell)
Eric Switzer (GSFC)
Jonas Zmuidzinas (Caltech)

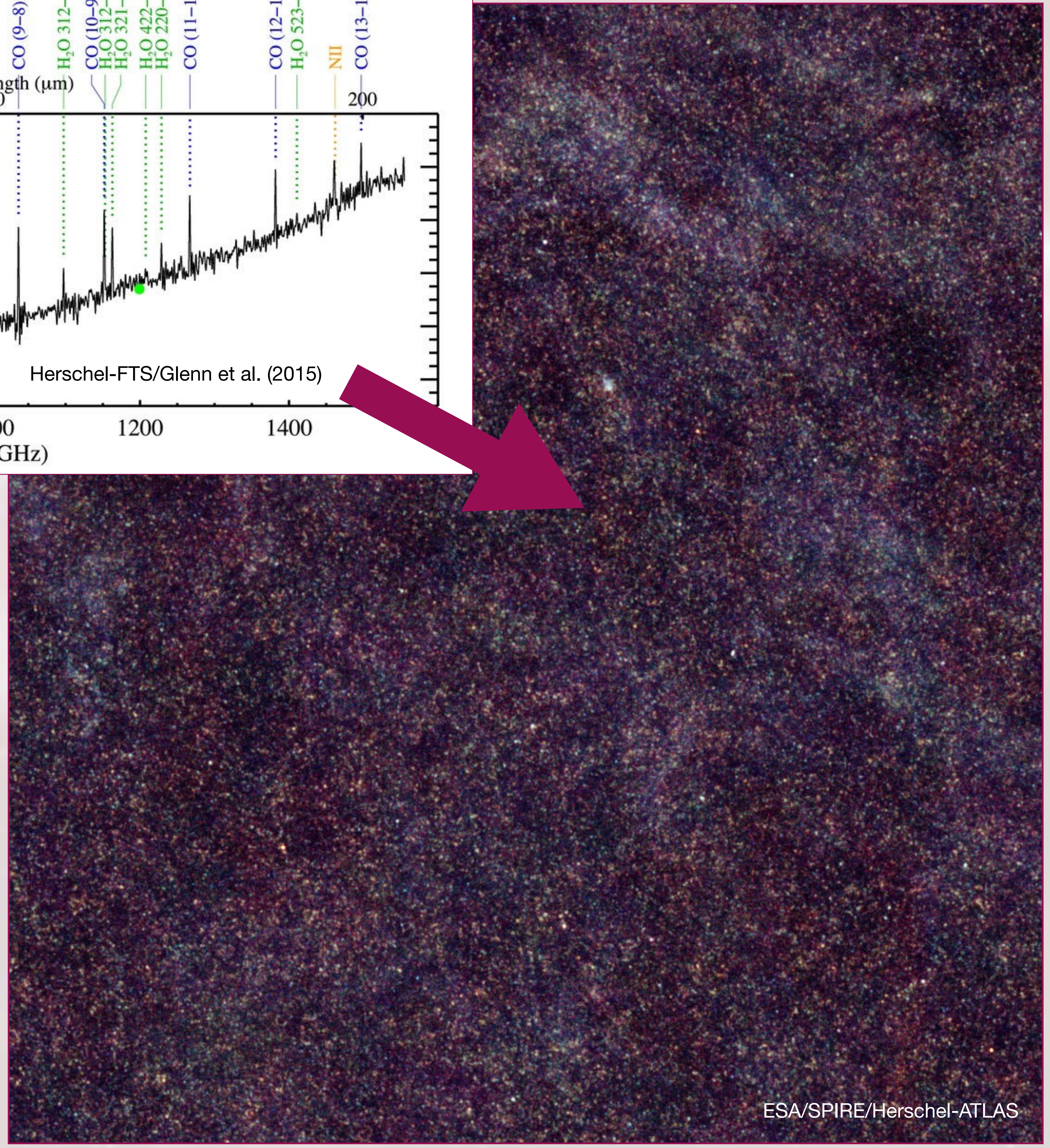
In Memoriam
Prof. Erik Shirokoff
1979-2023

The Dream

Everywhere, all the time, with infinite resolution

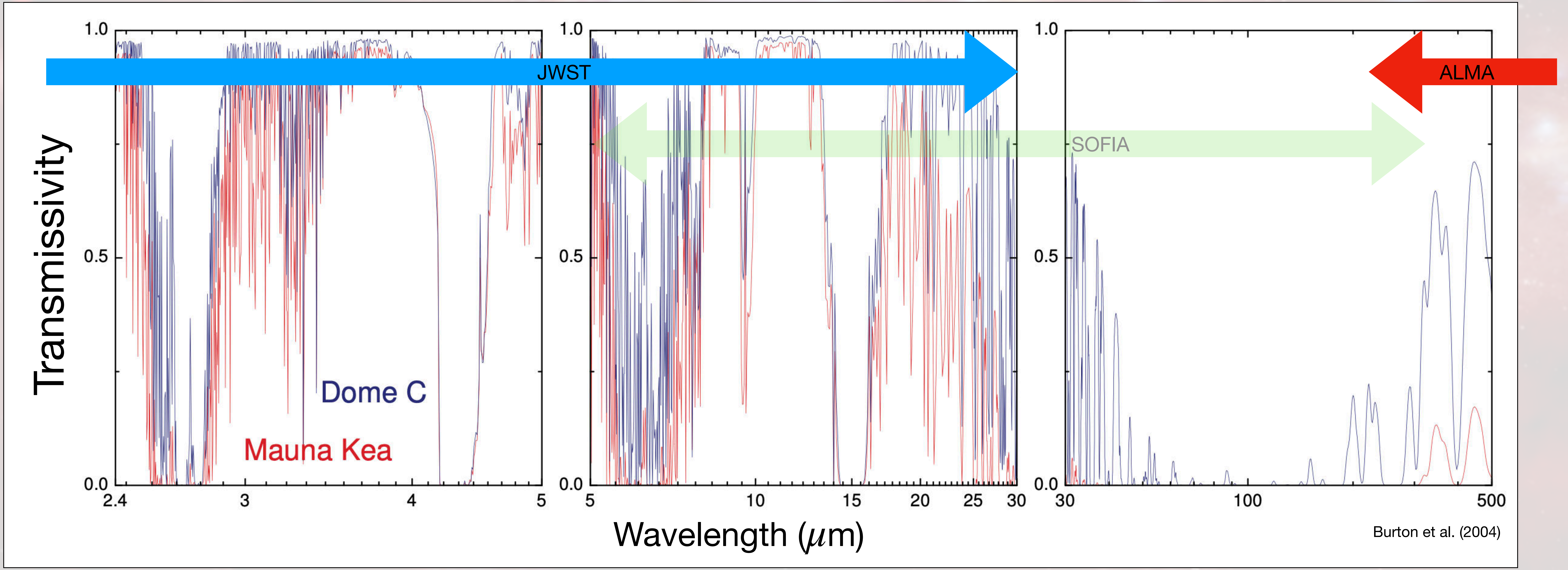






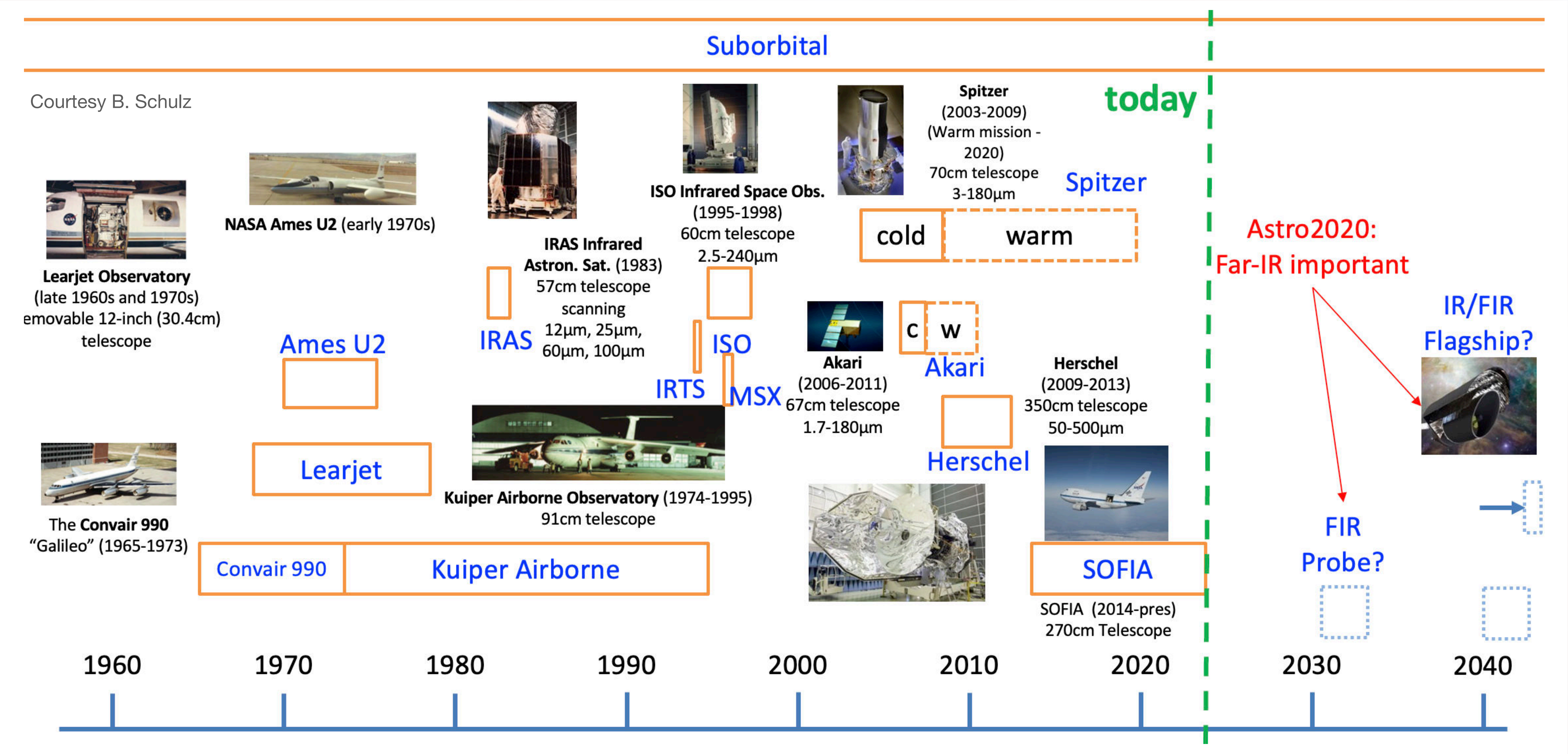
The Reality

The Atmosphere Is a Bear



The Reality

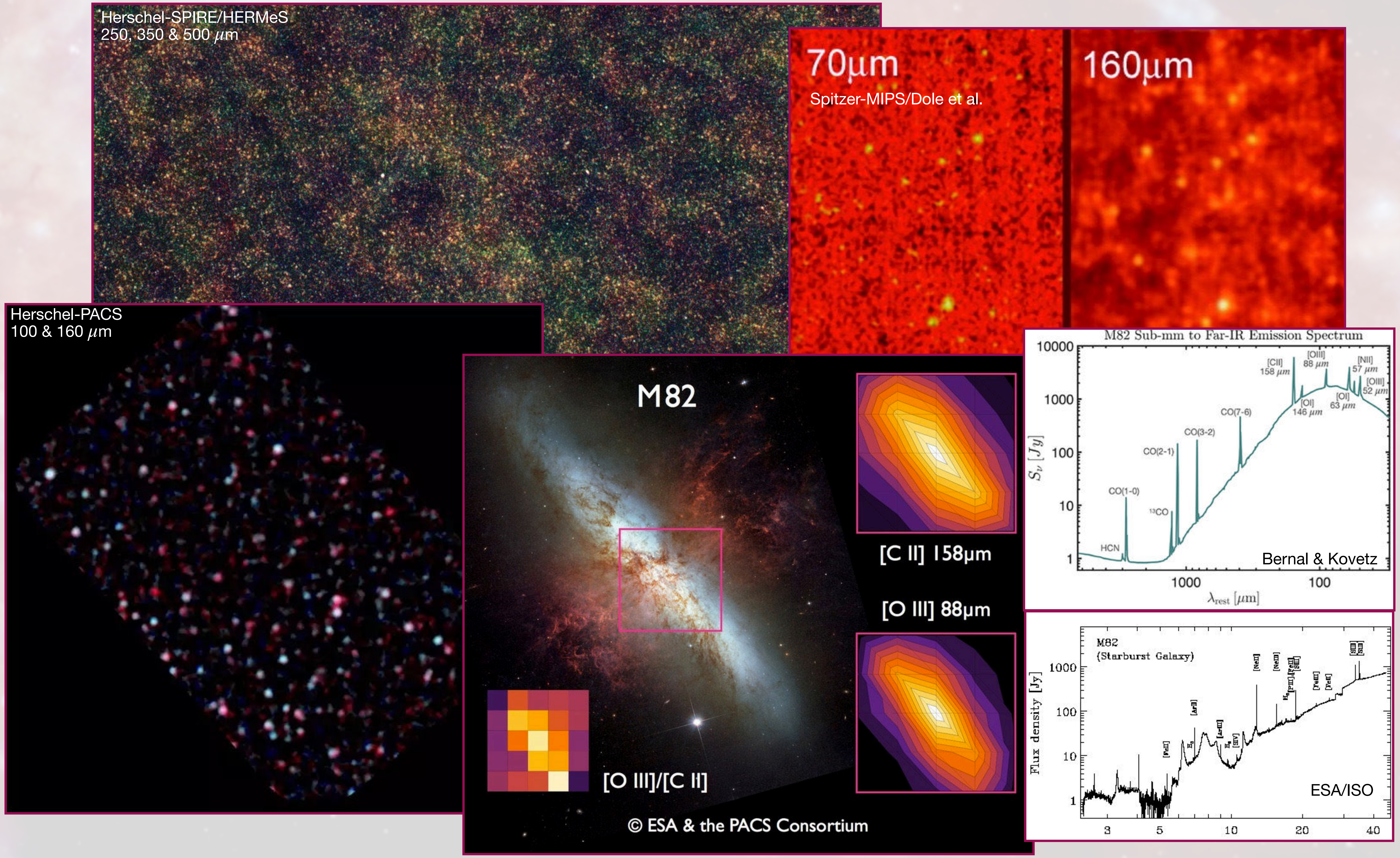
A Long Tradition of Measurements from Space



The Reality

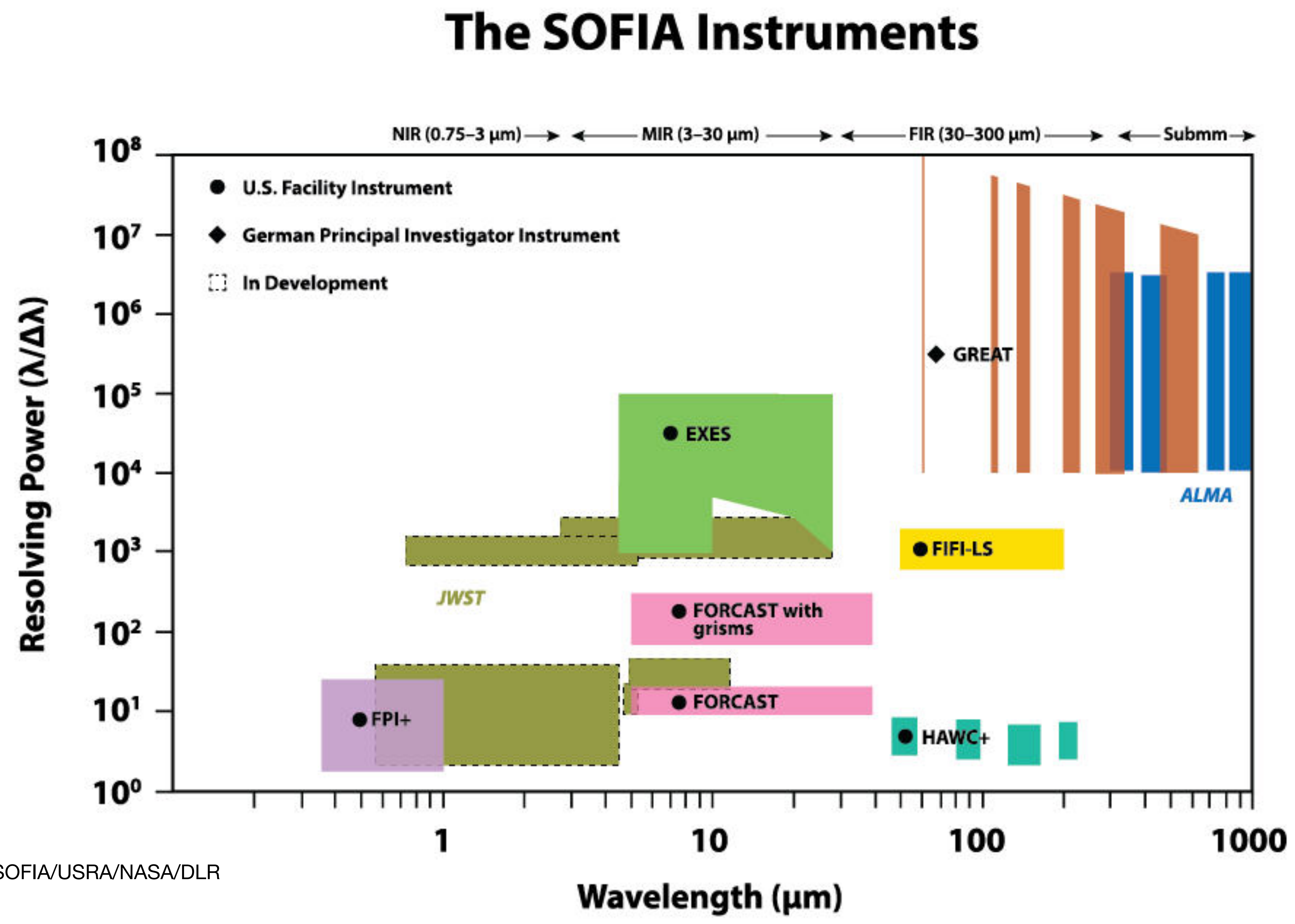
We Know Many Things, But There's Still More to Learn

- Broad-band photometry at sub-mm wavelengths done very successfully with Herschel, ground-based cameras.
- The trans-100 μm region is a little less well constrained.
- Spectroscopy in local objects done well; more distant universe remains understudied.



SOFIA's Role

Imaging Spectroscopy and Polarimetry from 45,000 ft



SOFIA/USRA/NASA/DLR

- KAO allowed single-pixel spectroscopy above (most of) the atmosphere.
- The "camera" era at sub-mm wavelengths started with SCUBA in the late 1990s.
  - Enormous step with Herschel, which mapped large areas of the sky in broad bands.
- Imaging spectroscopy has deep roots - pioneering work with various ground-based FTS and grating systems at sub-mm wavelengths. FIR with KAO, ISO, Spitzer, Herschel.
- SOFIA's (technical) legacy has largely been to enable the transition to many-pixel spectroscopy and polarimetry.

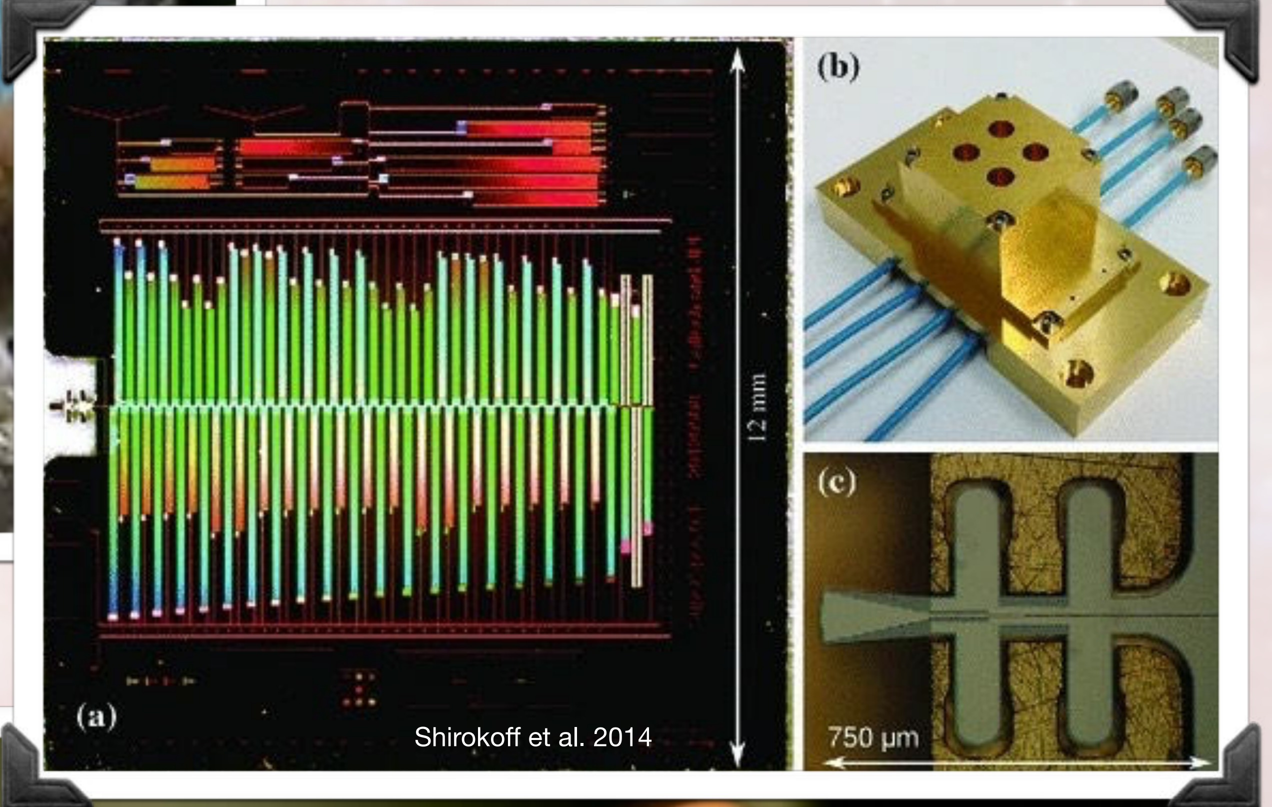
The Strategy
How Can We Realize the Dream?

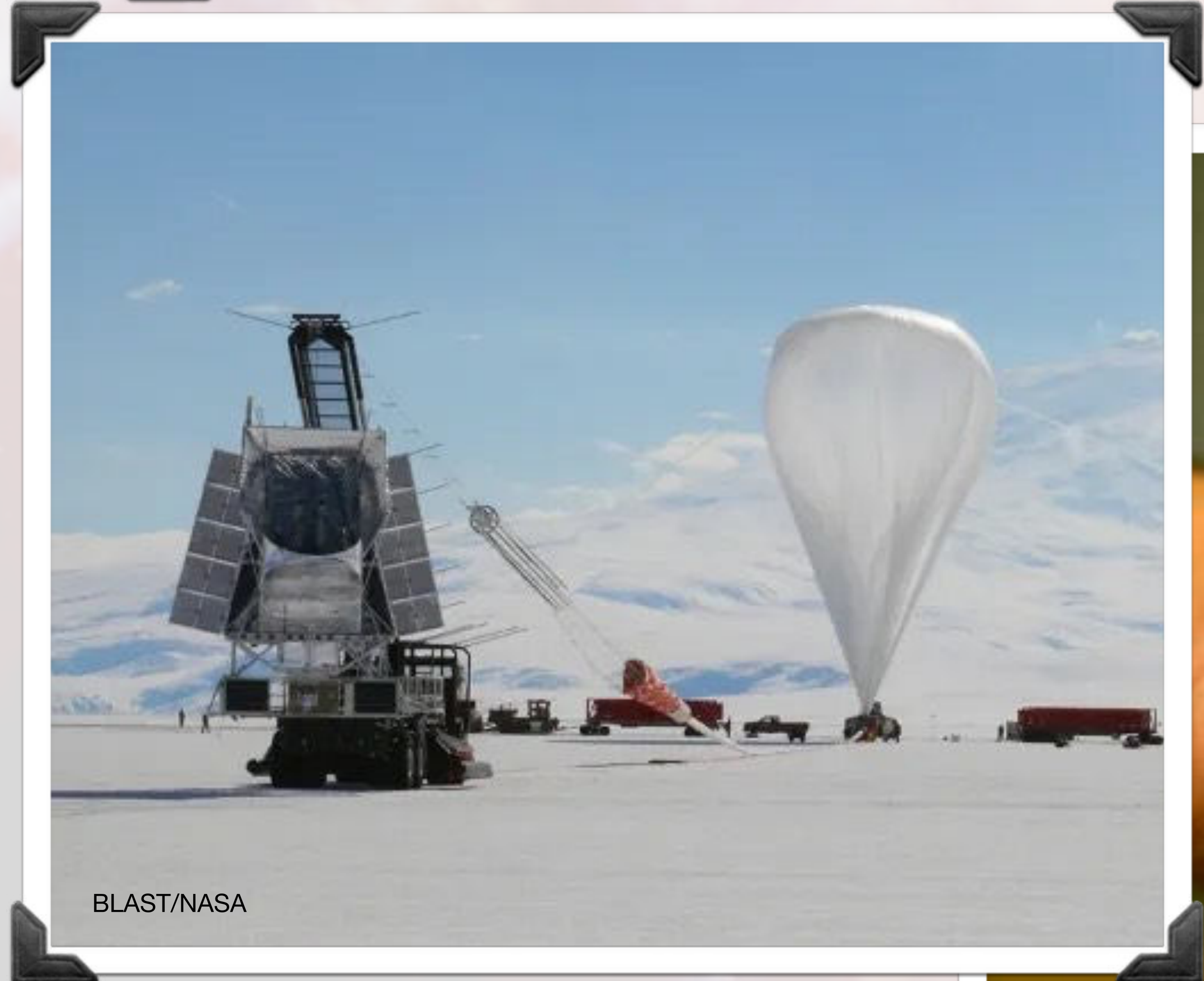
- The goal: wide-field imaging spectroscopy.
- The tools:
  - ➡ Telescope Architecture
  - ➡ Spectrometer Architecture
  - ➡ Detectors
  - ➡ Platforms

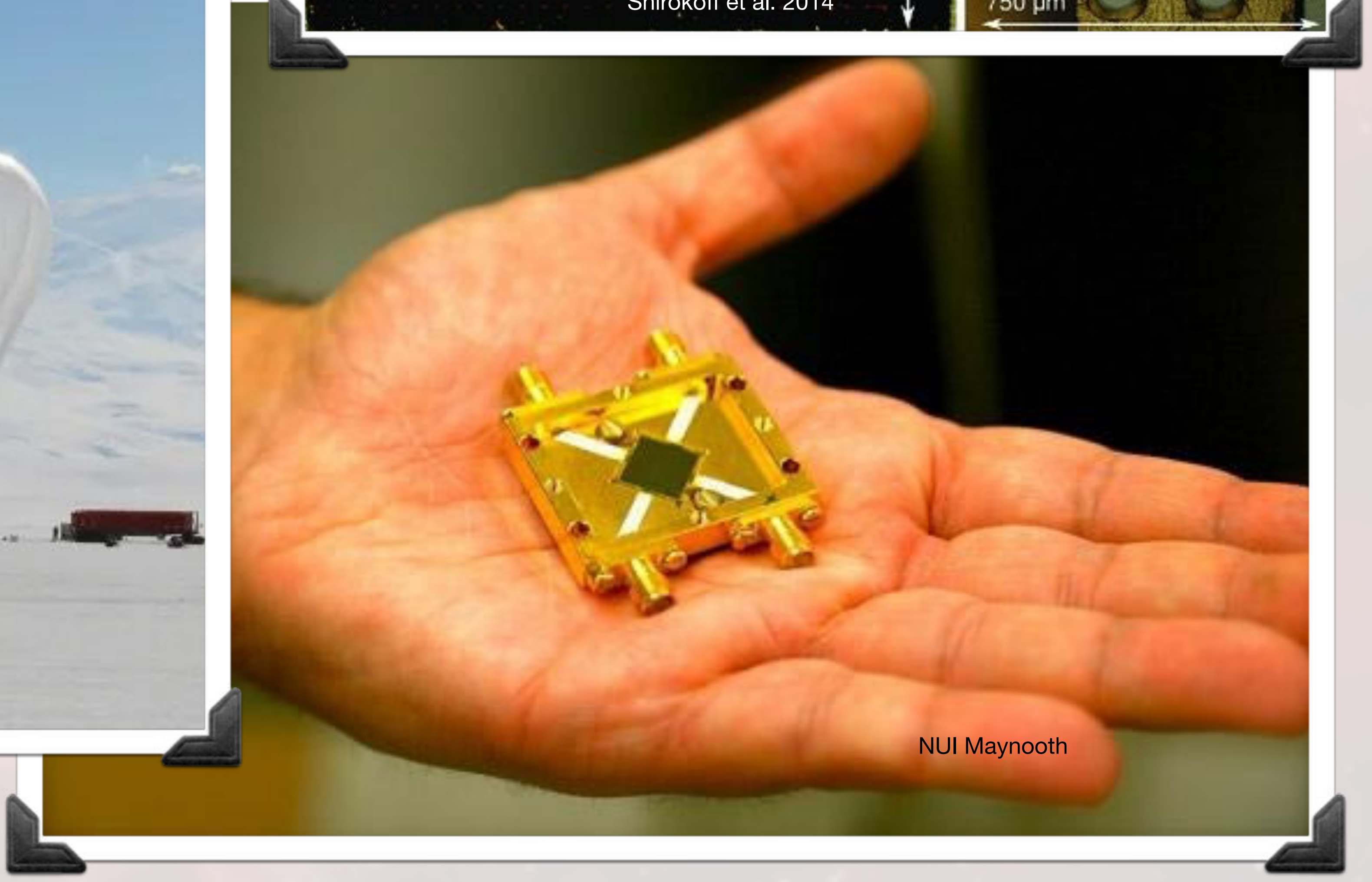
Fundamental Enabling Issues

What are the hurdles?

- Telescopes & cryocoolers are a pain.
- There is no “one size fits all” approach to spectroscopy.
  - Requires developing and providing deployment opportunities for multiple architectures.
- Detectors have to be built “by hand”, eliminating cost advantages of industrial development.
- Platforms are challenging and opportunities are infrequent.



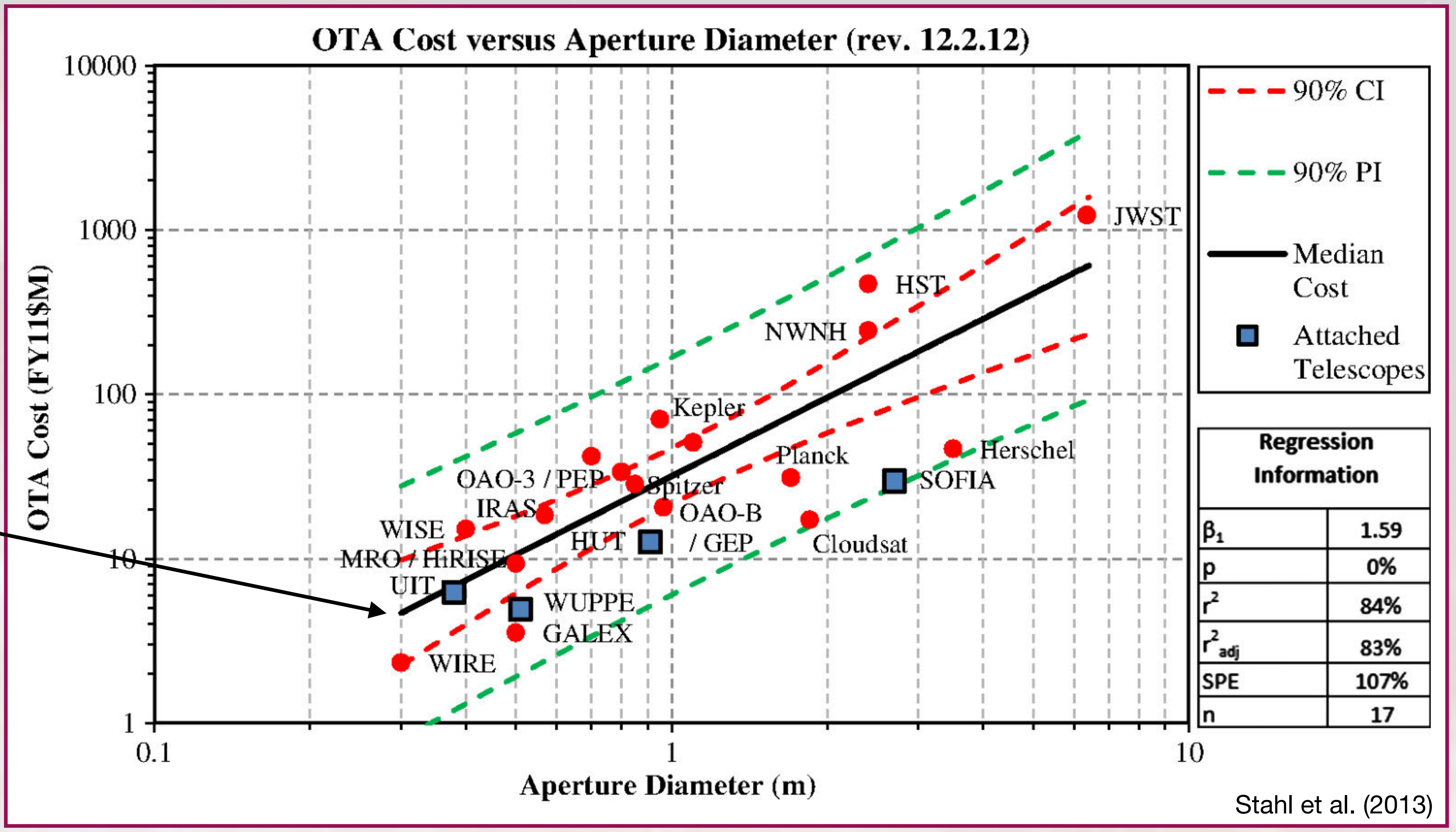




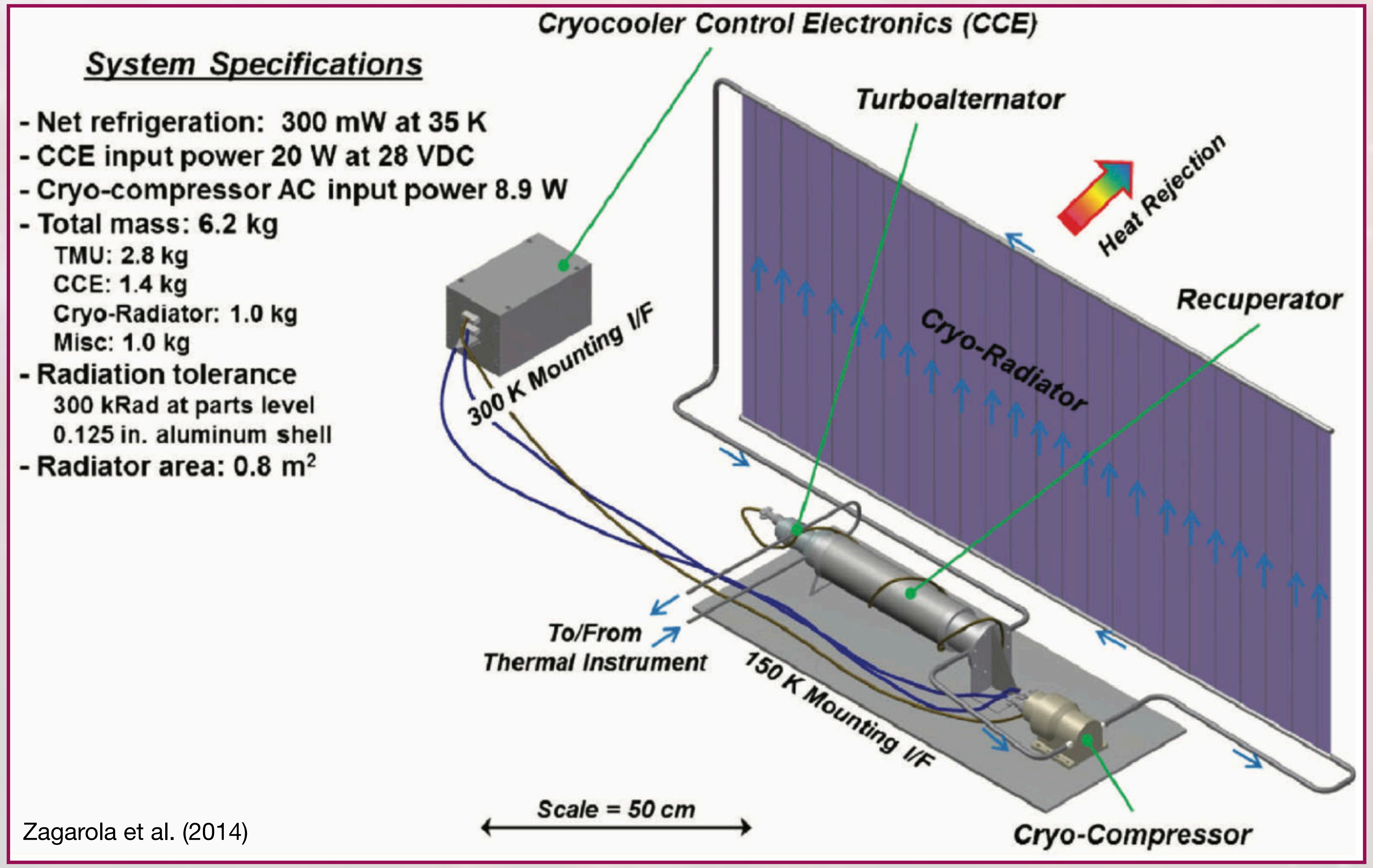
(Cooled) Telescopes

“Cold”

- Any telescope is space will be fighting Stahl’s Law.
- + Far-IR instruments will always need cryogenic cooling, often to sub-K temperatures at the detectors = expensive.
- We might also want to cool the telescope to lower the thermal background (eg. SPICA, MM-tron).
- Passive cooling and radiative approaches get to 10s of K in earth orbit.
- Cryomechanical coolers get us the rest of the way there, but power hungry → improve efficiency.
- *Continued investment in low-SWAP technologies will pay large dividends.*



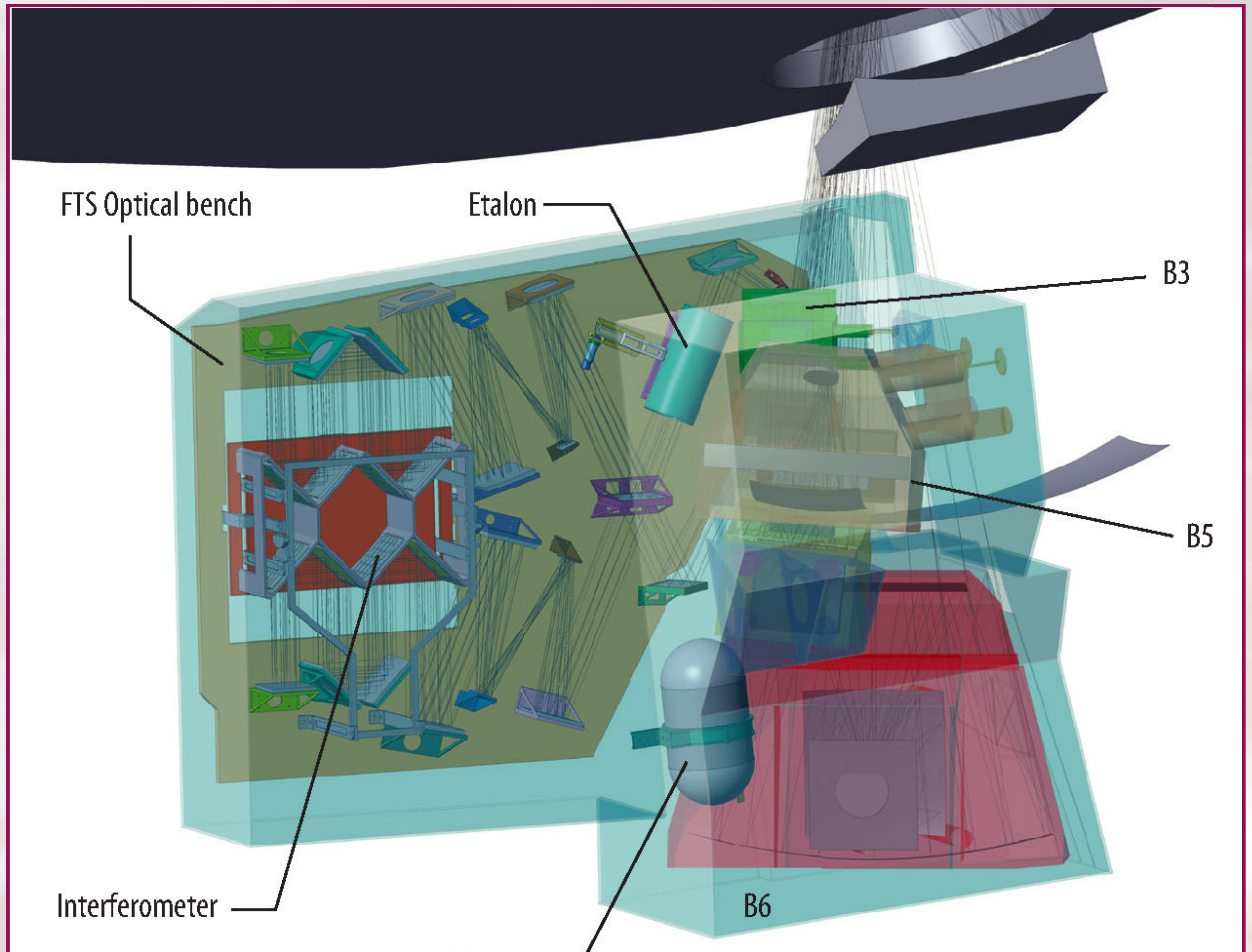
Stahl et al. (2013)



Zagarola et al. (2014)

Spectrometers
“Small”

- Technologies are largely already known:
  - Heterodyne (high R)
  - Gratings (inc. Echelle)
  - Fourier Transform Systems
  - Etalons
  - On-chip methods
  - + combinations thereof.

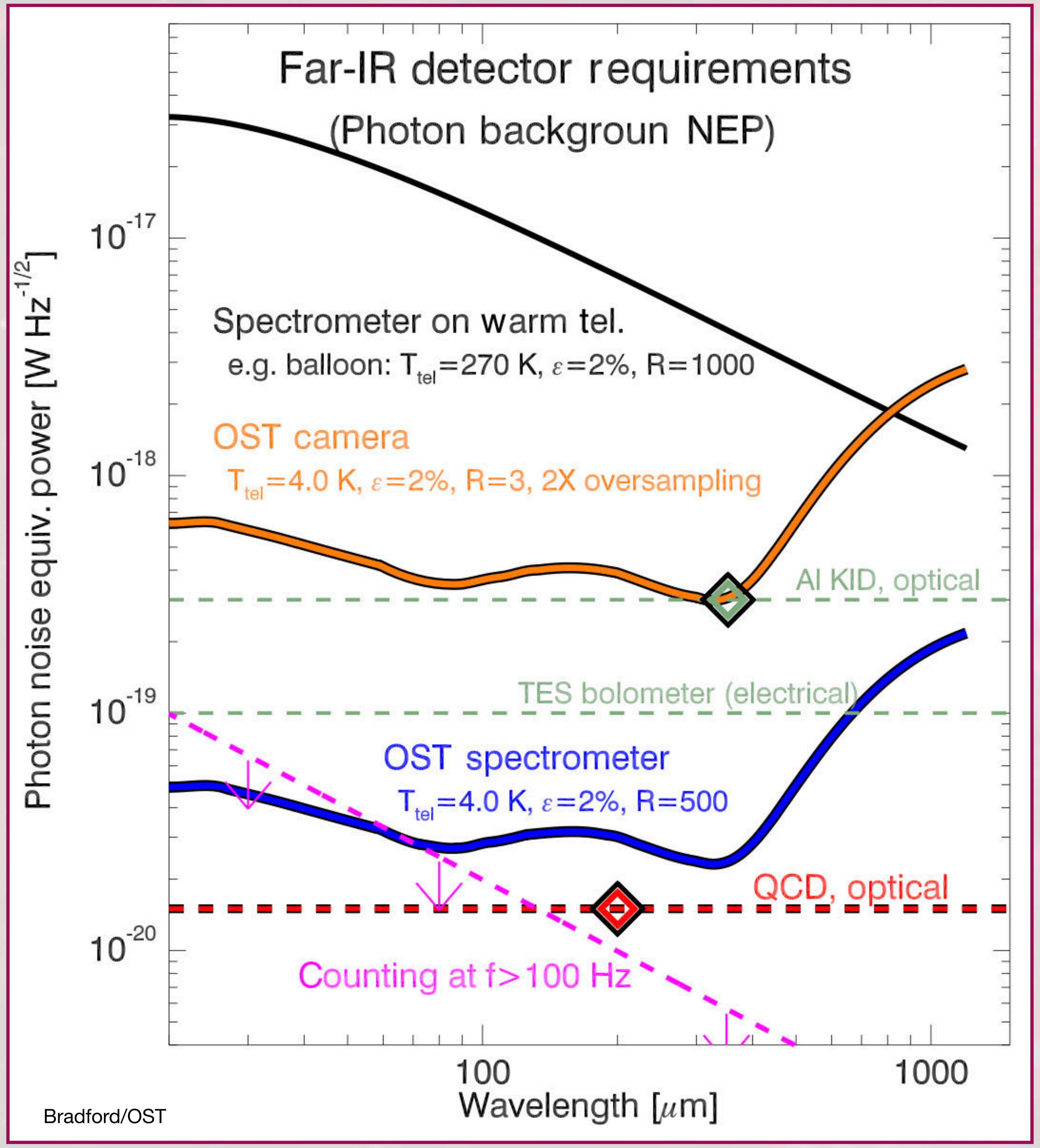


Origins Concept Study

- These technologies have high heritage, so (mostly) becomes more about engineering and fabrication techniques than fundamental physics.
- Technologies to couple light into waveguide and similar structures may benefit from more investment, particularly at shorter wavelengths where physics transitions.

Detectors

“Plentiful”

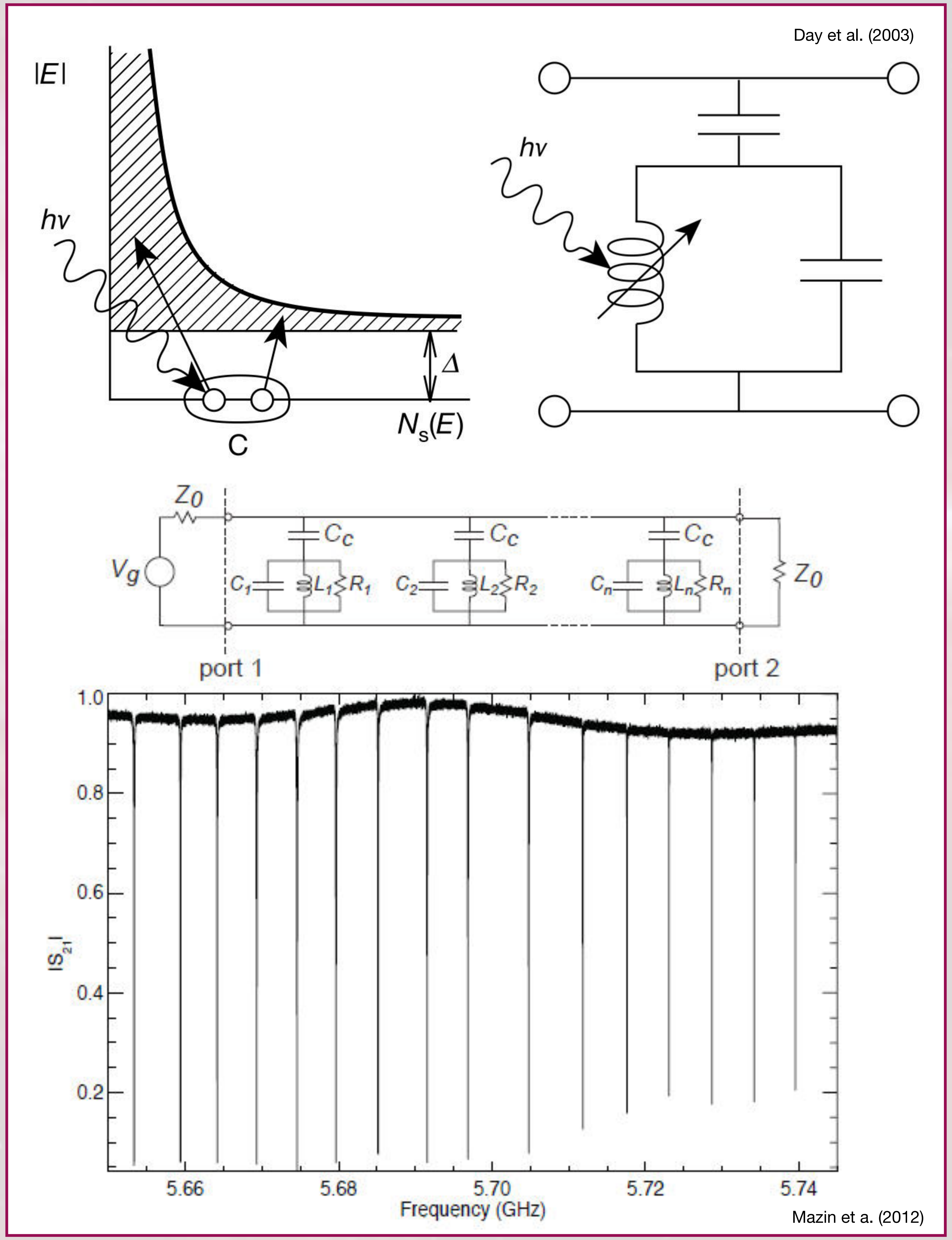


- We have had good sub-mm direct detectors for a long time (e.g. Herschel, Planck, SOFIA).
- Heterodyne devices are also quantum-limited in the sub-mm, and quite close at shorter wavelengths.
- Over the past 20 years, we have pushed NEPs with Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs).
- For imaging spectroscopy, the current favorite seems to be KIDs. This has to do with (relative) ease of readout and multiplexing.

Detectors

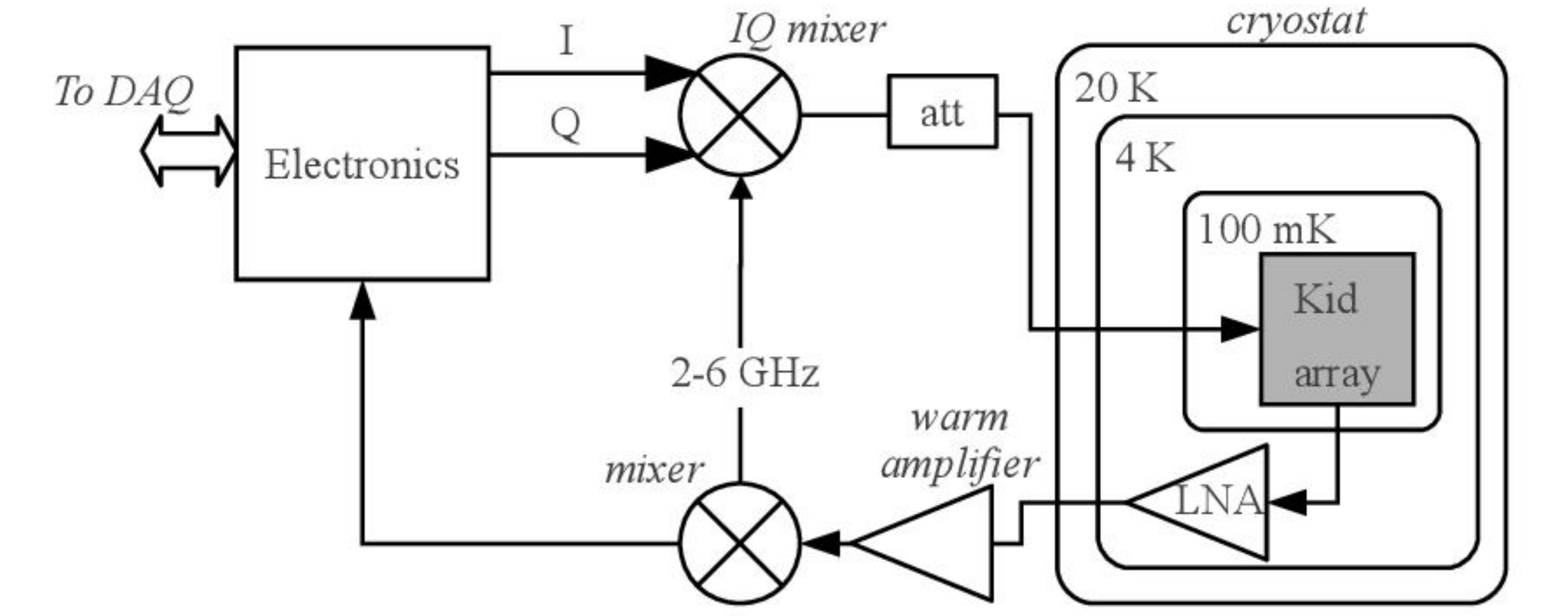
“Plentiful”

- Kinetic Inductance Device pixel is a lithographed superconducting inductor-capacitor resonator circuit.
- Photon absorbed by inductor breaks Cooper pairs to cause a change in inductance.
- Change in resonance can be probed by external electronics and converted to photon flux via calibration.
- Multiplexing achieved by varying resonator properties and probing every tone.

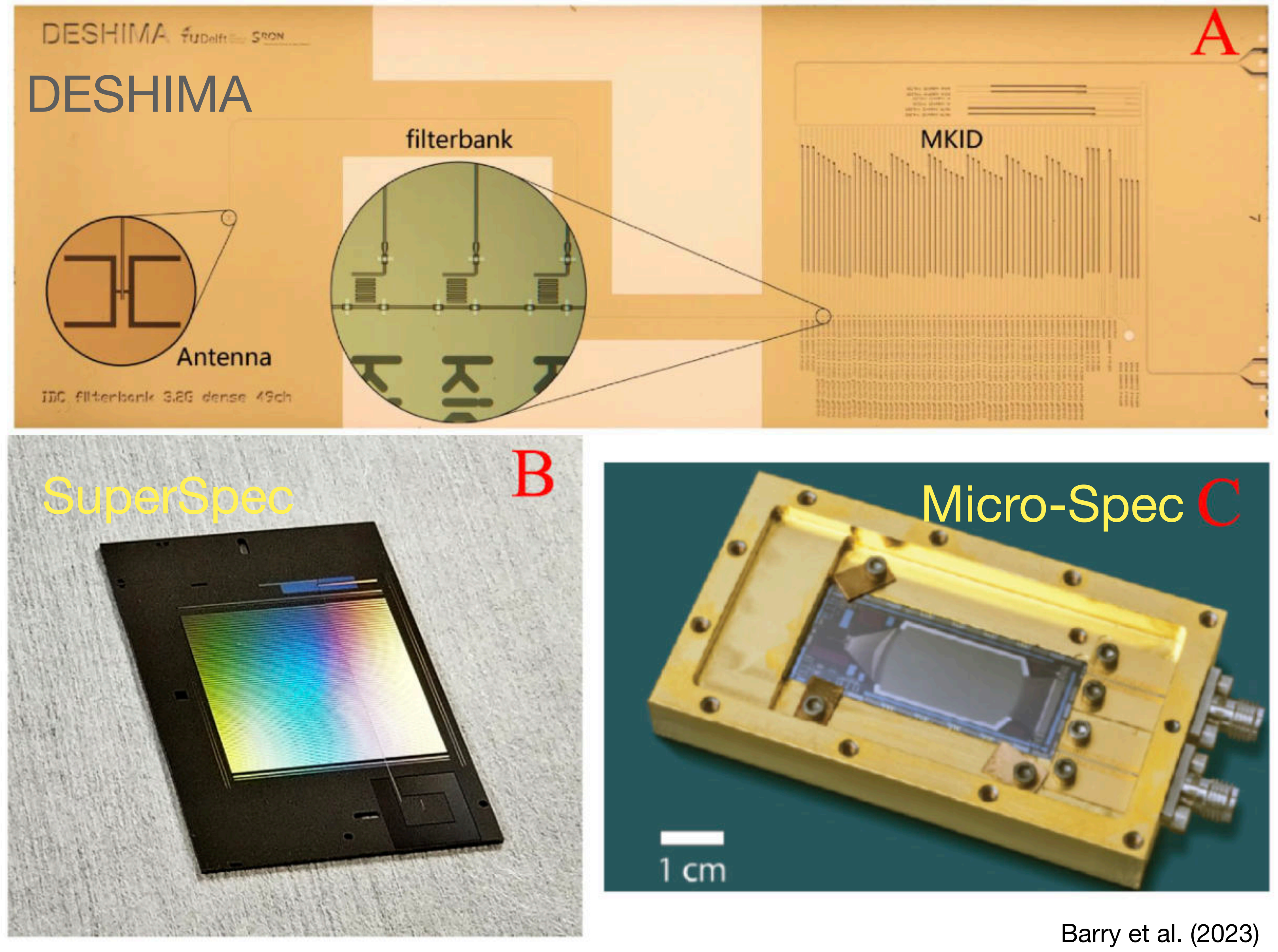


Detectors

“Plentiful”



Bourrion et al. (2013)



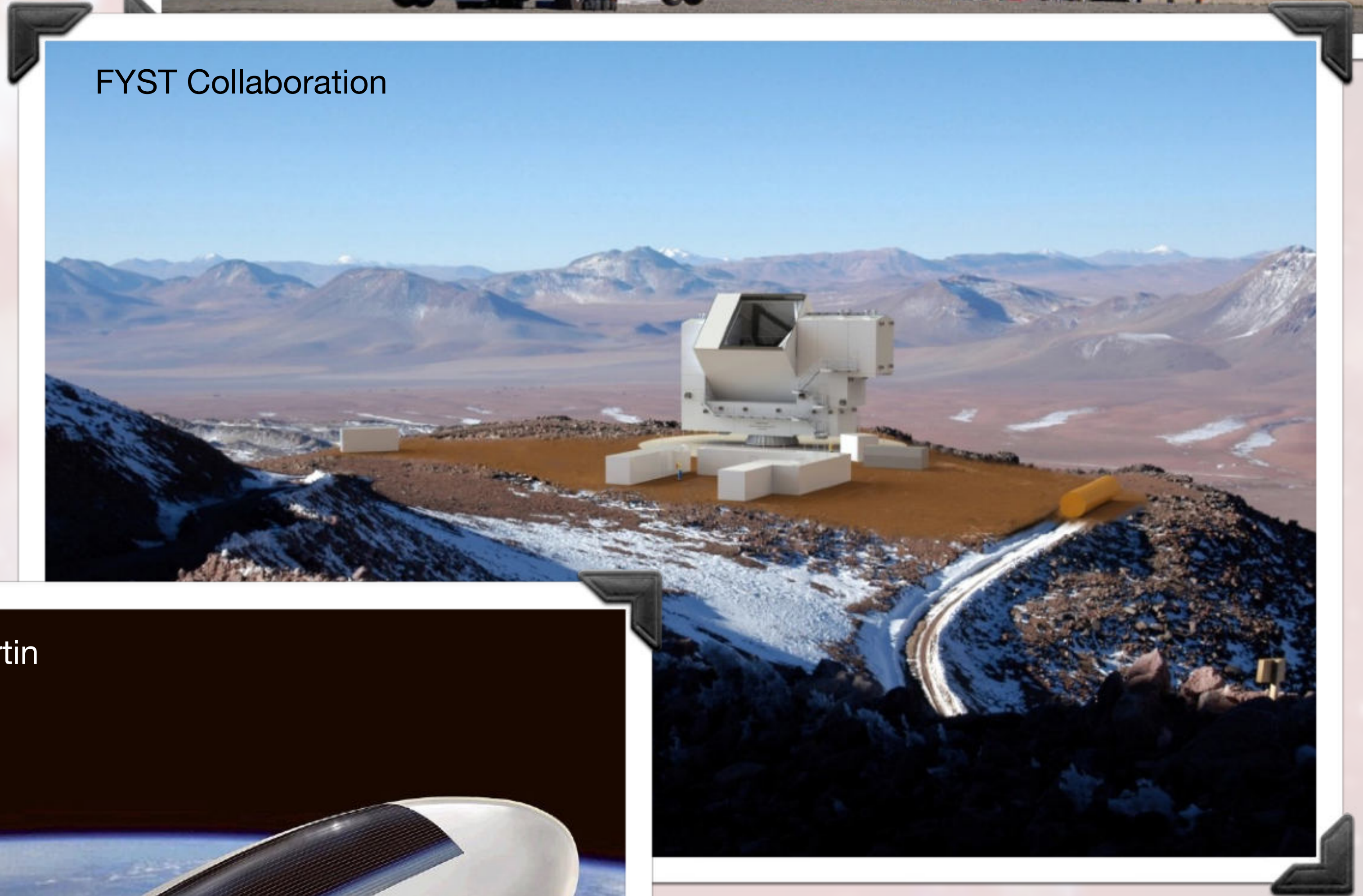
Barry et al. (2023)

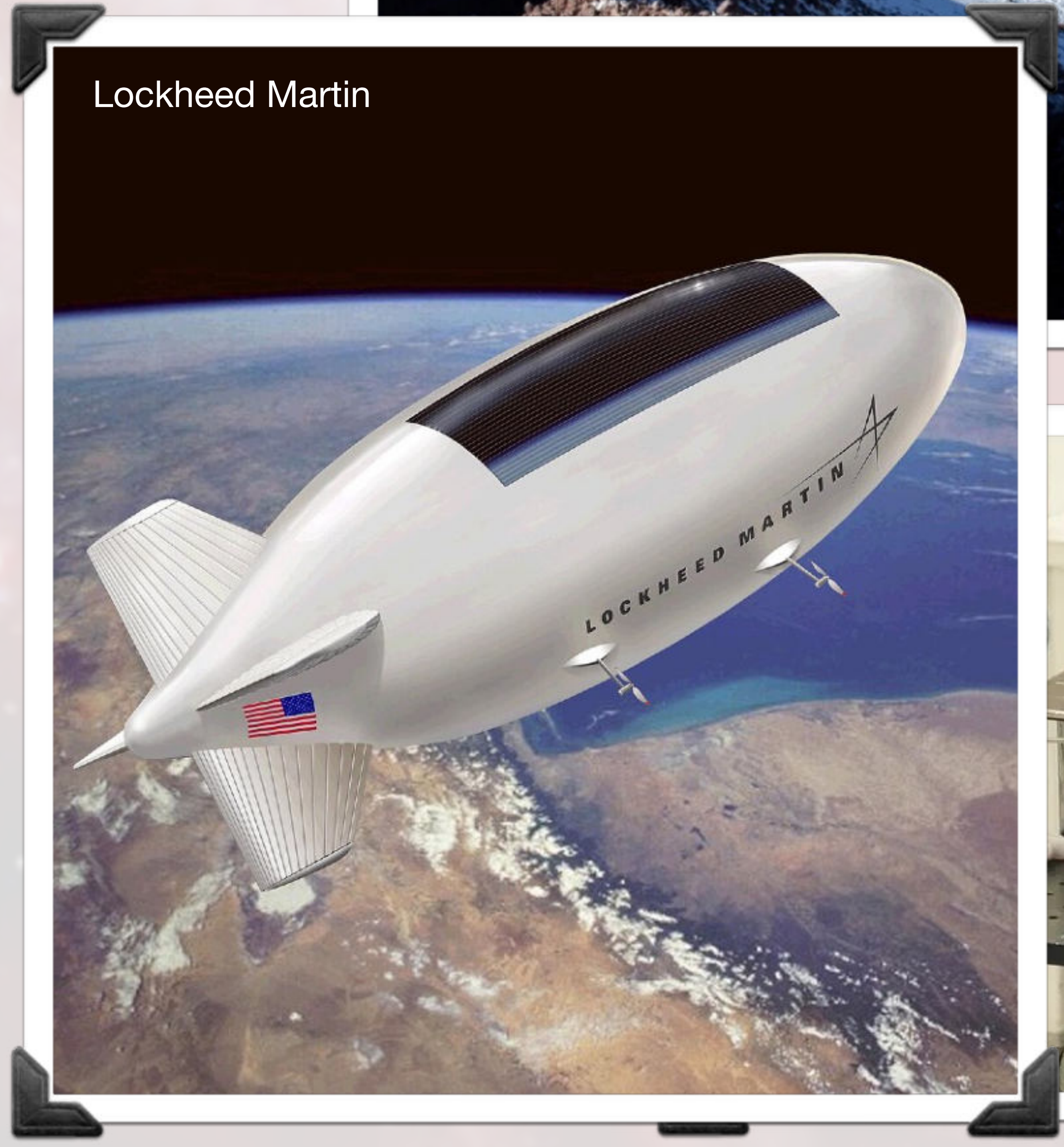
- Progress is happening quickly!
- Current NEPs getting into the < 10^{-19} W $Hz^{-1/2}$ range required for cooled-telescope spectroscopy.
- The push now is to go to thousands of pixels.
- Requires changes to how we think about cost per detector - need to fabricate and read out arrays for < $10/detector.
- The problem now seems to be more engineering than fundamental feasibility (phew!).

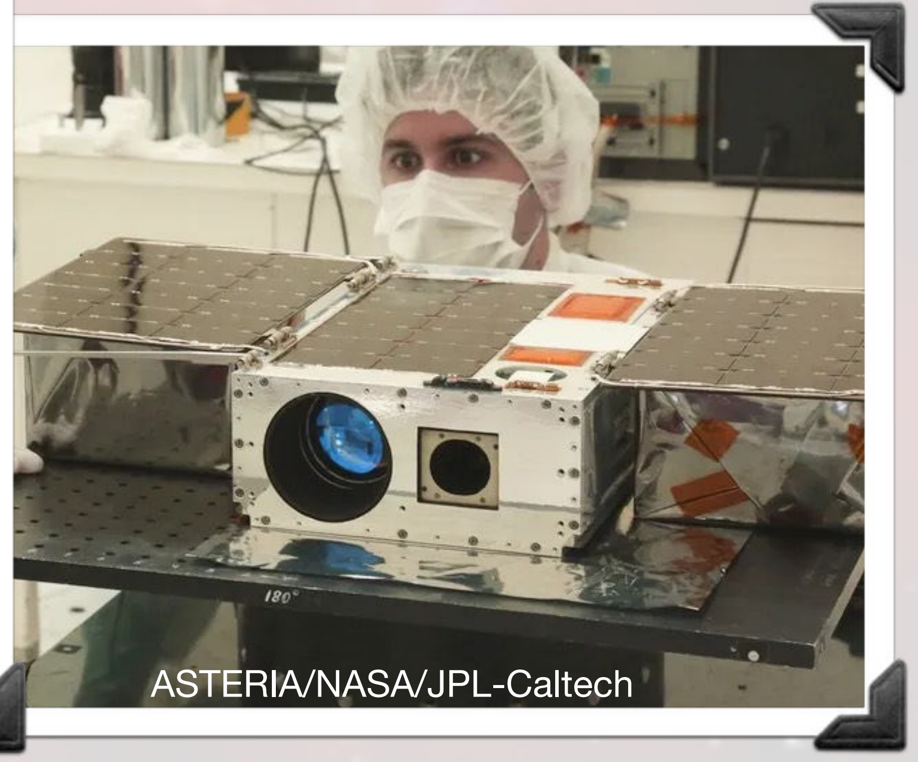
Platforms

How to Beat the Atmosphere

- Orbital Missions remain the “Big Game” of the Far-IR community (e.g. APEX Missions, future Probe or Flagship-class opportunities).
- Balloons permit long hang times at ~30km, and new Far-IR missions are selected every 2-3 years.
- Sub-orbital rockets also available, though niche.







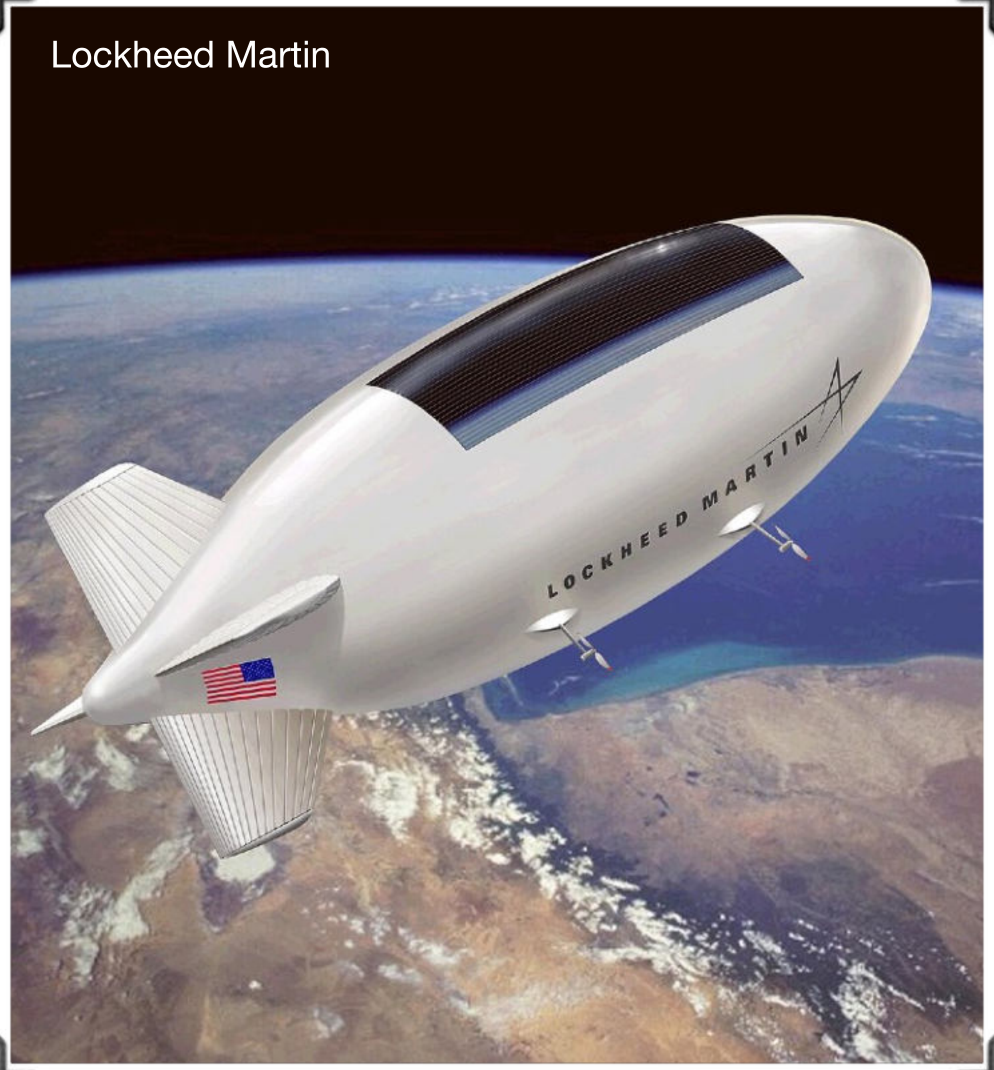
Platforms

How to Beat the Atmosphere

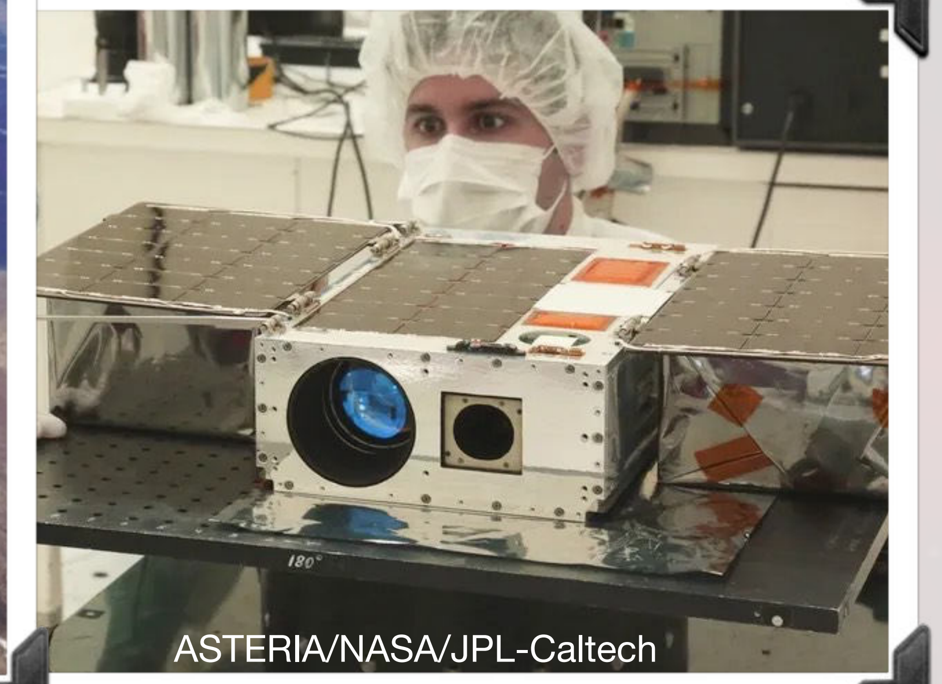
- Ground-based becoming more feasible with the opening of very high, dry sites. Especially useful for high-*R* heterodyne in THz.
- Observatory-class balloons or “airships” have been discussed; would need the community to get behind these concepts to make progress. Cost?
- Possibly SmallSats? Would need investment in miniature cryogenic technologies.


NASA


FYST Collaboration



Lockheed Martin

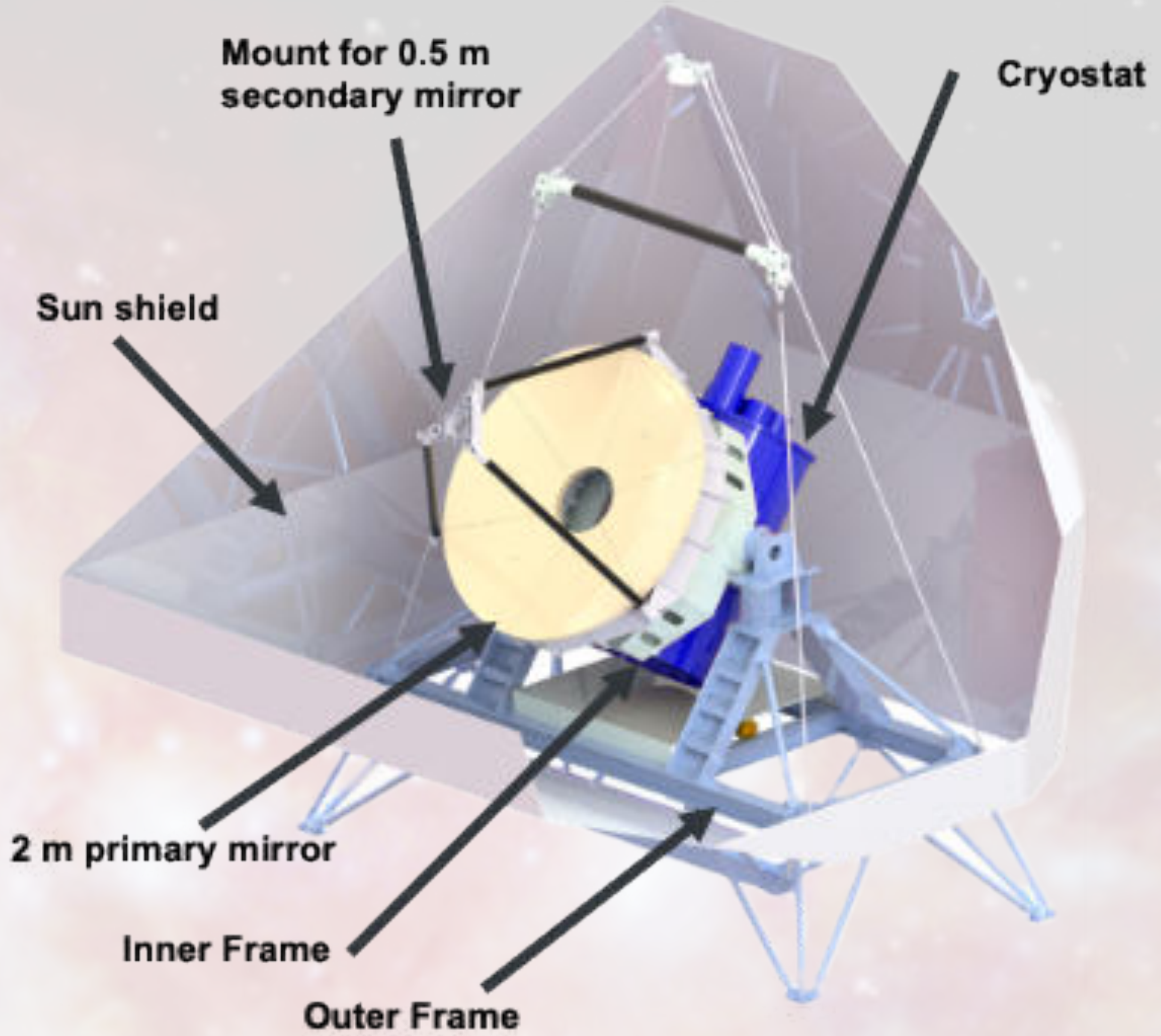

ASTERIA/NASA/JPL-Caltech

Terahertz Intensity Mapper (TIM)

A stepping-stone towards future IR space observatories

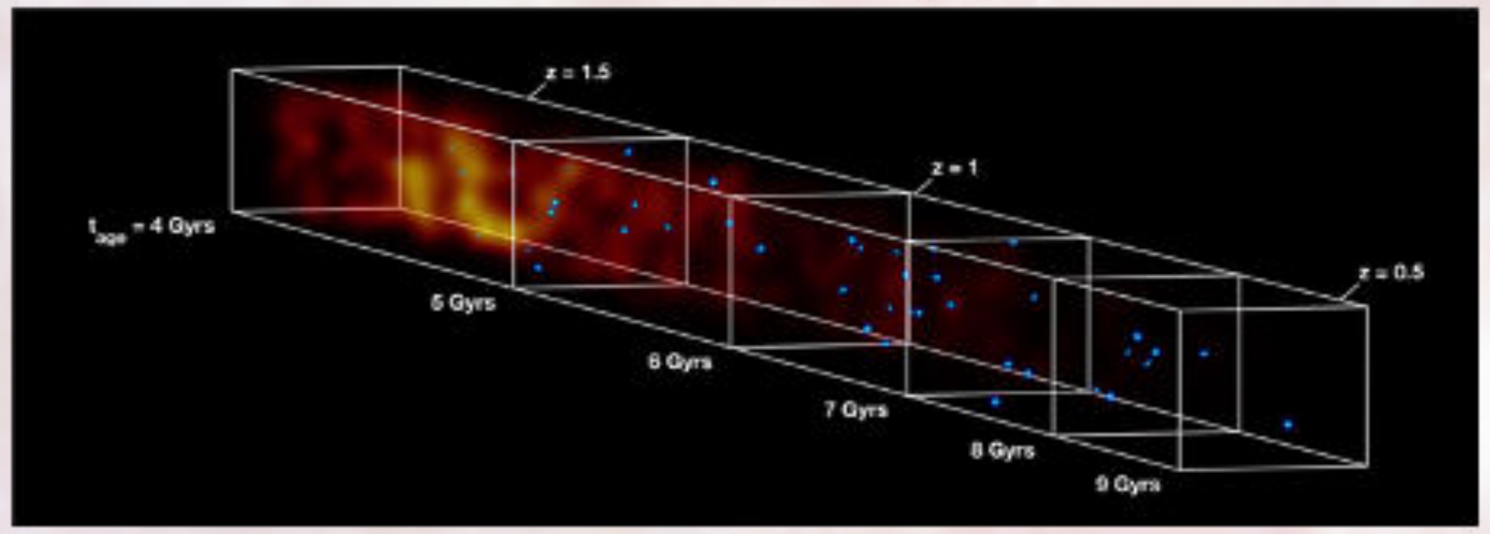
Stratospheric **balloon** (deploy 2025) to study **star formation** and the **dust-obscured universe** across space and time

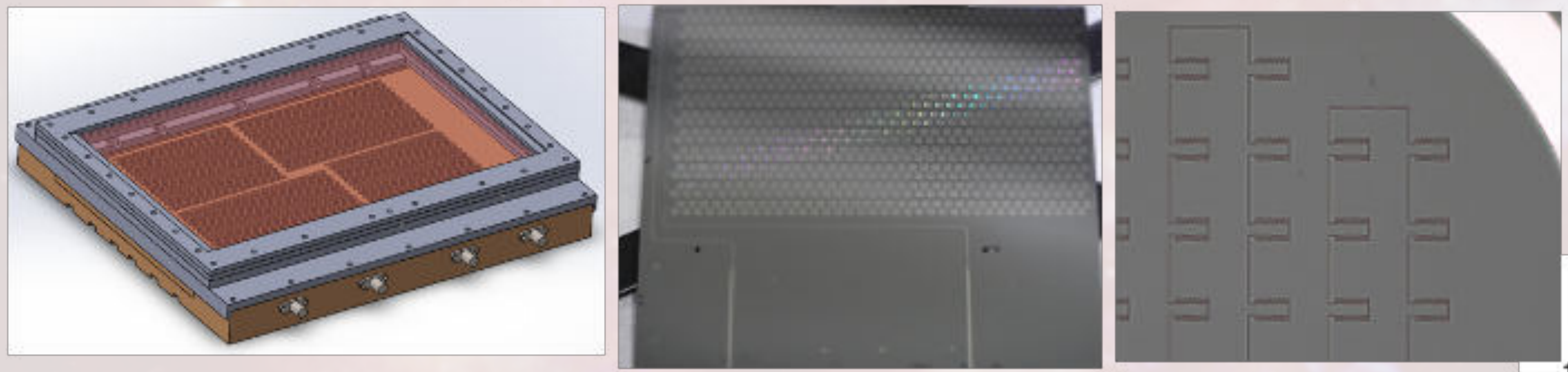
- [CII] (*158 µm*) luminosity function and power spectrum from pathfinding demonstration of FIR **line intensity mapping (LIM)**
- ~100 direct [CII] detections, wealth of stacking analyses on [CII], [NII], [OI], [OIII]



Demonstrate FIR spectroscopy from a space-like environment

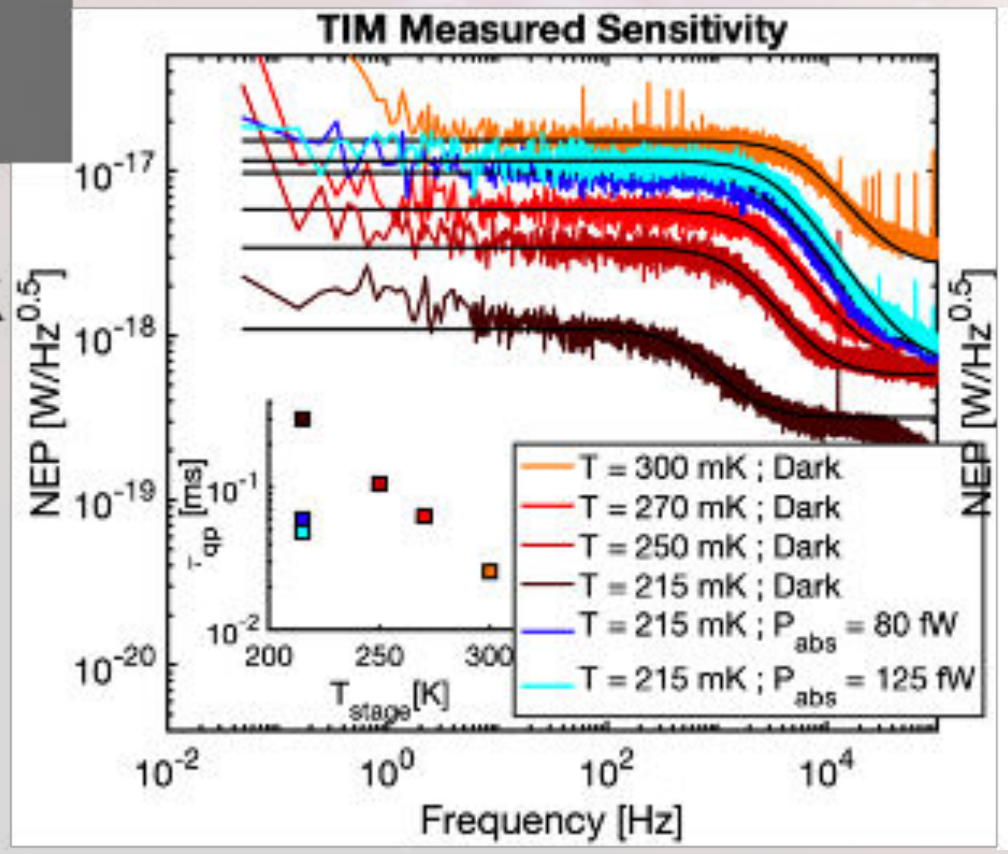
- Two grating spectrometers spanning 240-420 µm (R~250)
- 2m warm primary; 1 degree FOV slit; 25" spatial resolution
- Developing characterization techniques, e.g., photogrammetry, …





Low-noise **kinetic inductance detectors (KIDs)** for the FIR

- Dual 3600-pixel KID arrays (*JPL*), feedhorn-coupled (*ASU*)
- Optimized, versatile absorber design (*UIUC, JPL*)
- RFSoC-based frequency-domain readout system (*ASU*)
- Demonstrated single-pixel performance, >90% yield on first 900px quadrant *⇒ First flight array deliveries in 2023*



NASA APRA, PI: J. Vieira (U. Illinois)

Vieira et al., arXiv 2009.14340

Marrone et al., Proc SPIE (2022)

Janssen et al., J. Low Temp. Phys (2022)

Nie et al., J. Low Temp. Phys (2022)

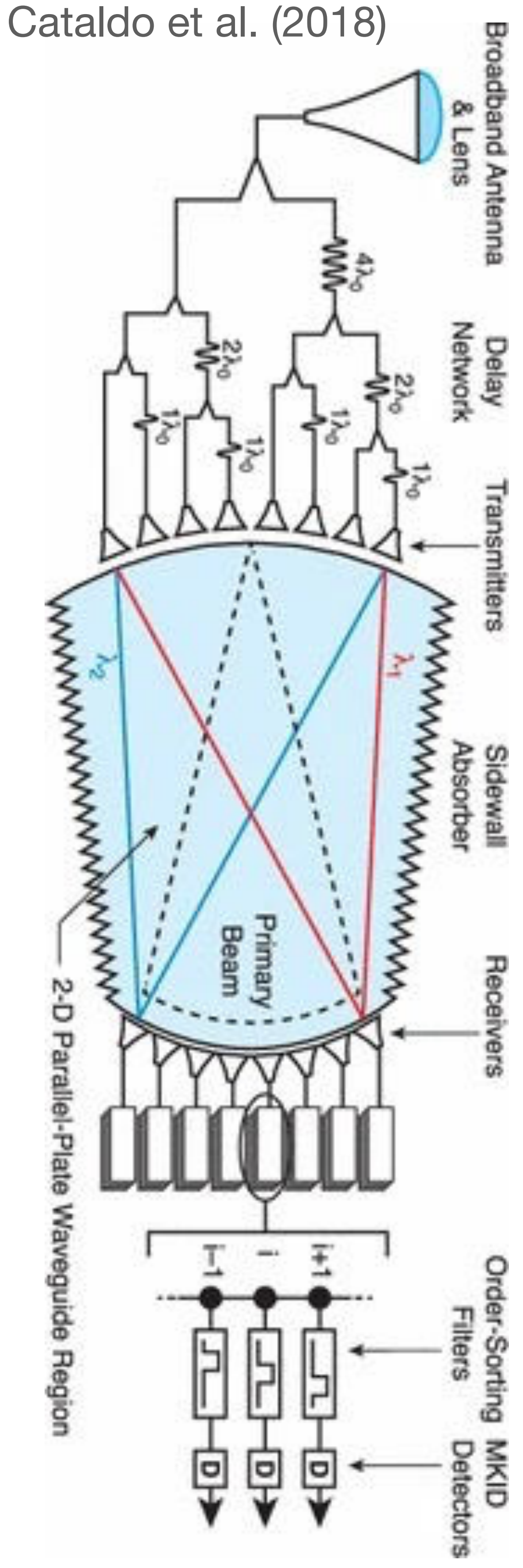
ILLINOIS | JPL Jet Propulsion Laboratory California Institute of Technology | The University of Arizona | ASU | Penn

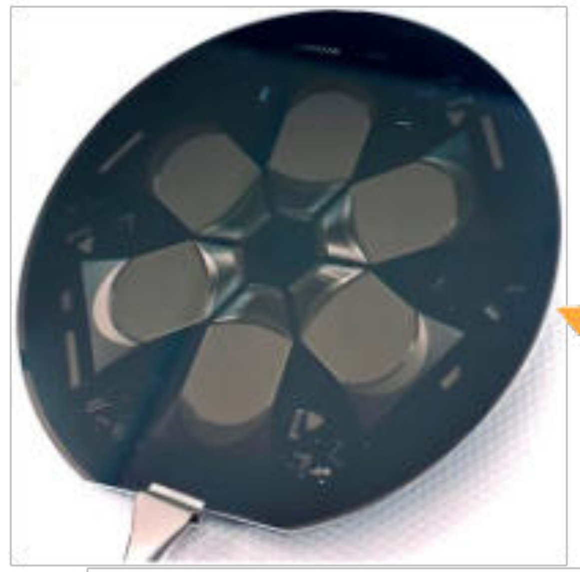
Courtesy J. Filippini

EXCLAIM Mission

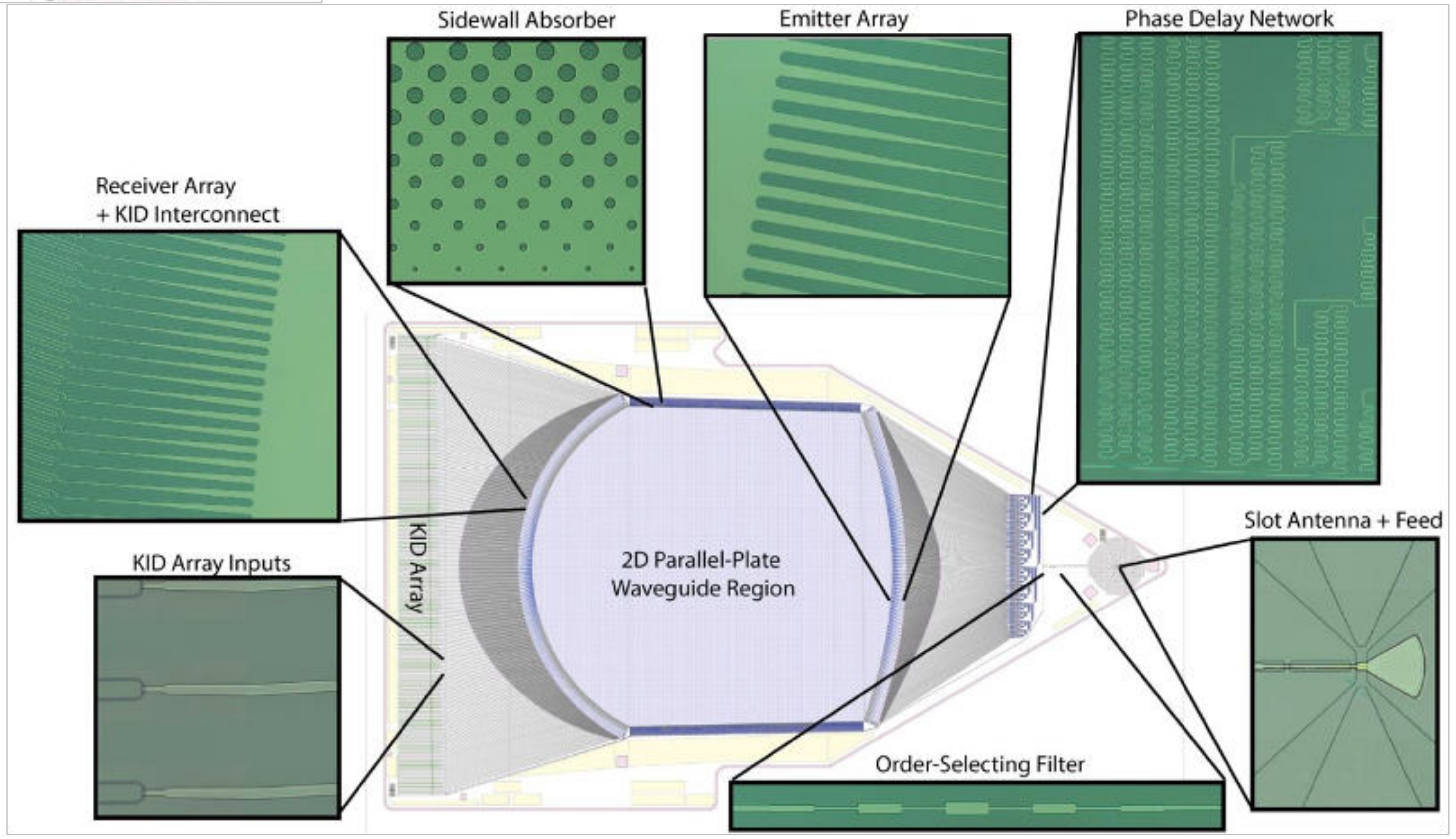
Technology Development

Cataldo et al. (2018)

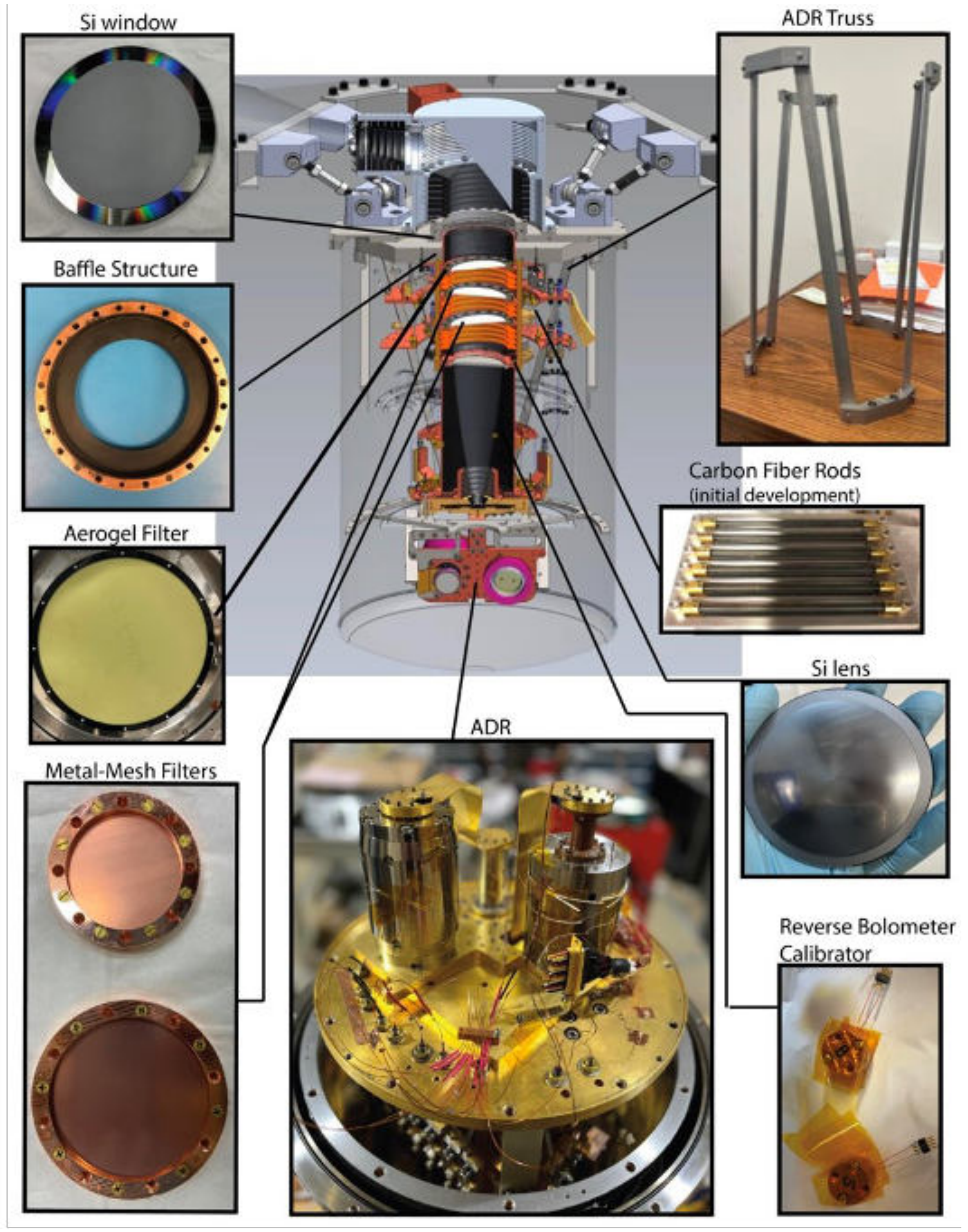




- Goal: Integrated star formation rate through line intensity mapping (CO/CII) in cross-correlation with BOSS galaxy survey.
- All-cryogenic (1.7 K, LHe) telescope and conventional balloon flight, focal plane cooled to 100 mK by continuous ADR in receiver (right).
- Key enabling technology: integrated spectrometer 420-540 GHz, R=512, kinetic inductance detectors. Components below:



Courtesy E. Switzer

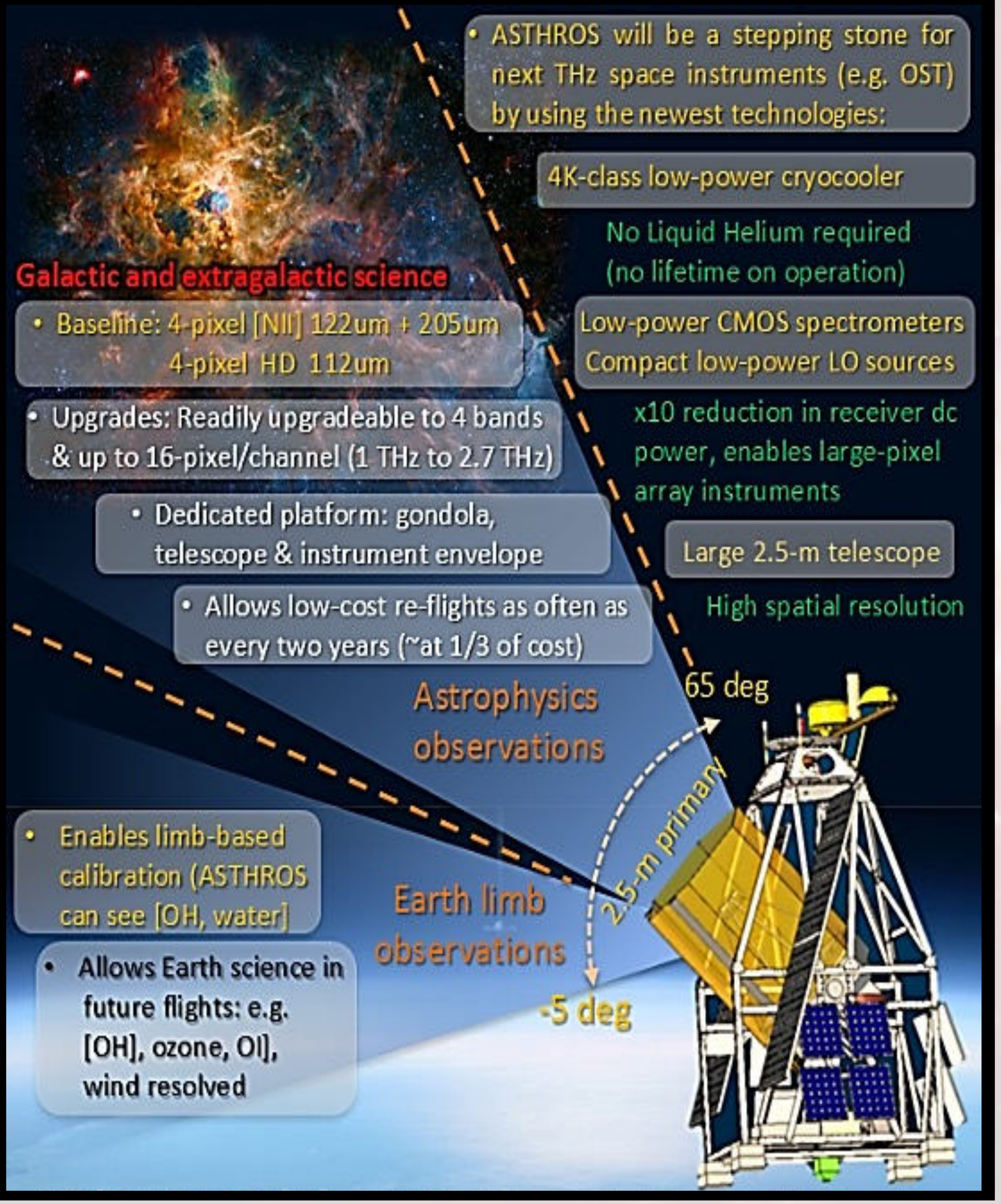


ASTHROS Balloon Mission

The Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS) is a suborbital balloon mission to enable detailed three-dimensional mapping of ionized gas in star forming regions in the Milky Way **and external galaxies** via simultaneous observations of the [NII] 122μm (2.675 THz) and 205μm (1.461 THz) fine structure lines of ionized nitrogen.

ASTHROS will be a **2.5m telescope** carried by a zero pressure balloon to a flight altitude of 130,000 feet and will produce high spectral resolution, high spatial dynamical range maps of the ionized gas component in a selected sample of star forming regions during an Antarctica flight in Dec. 2024.

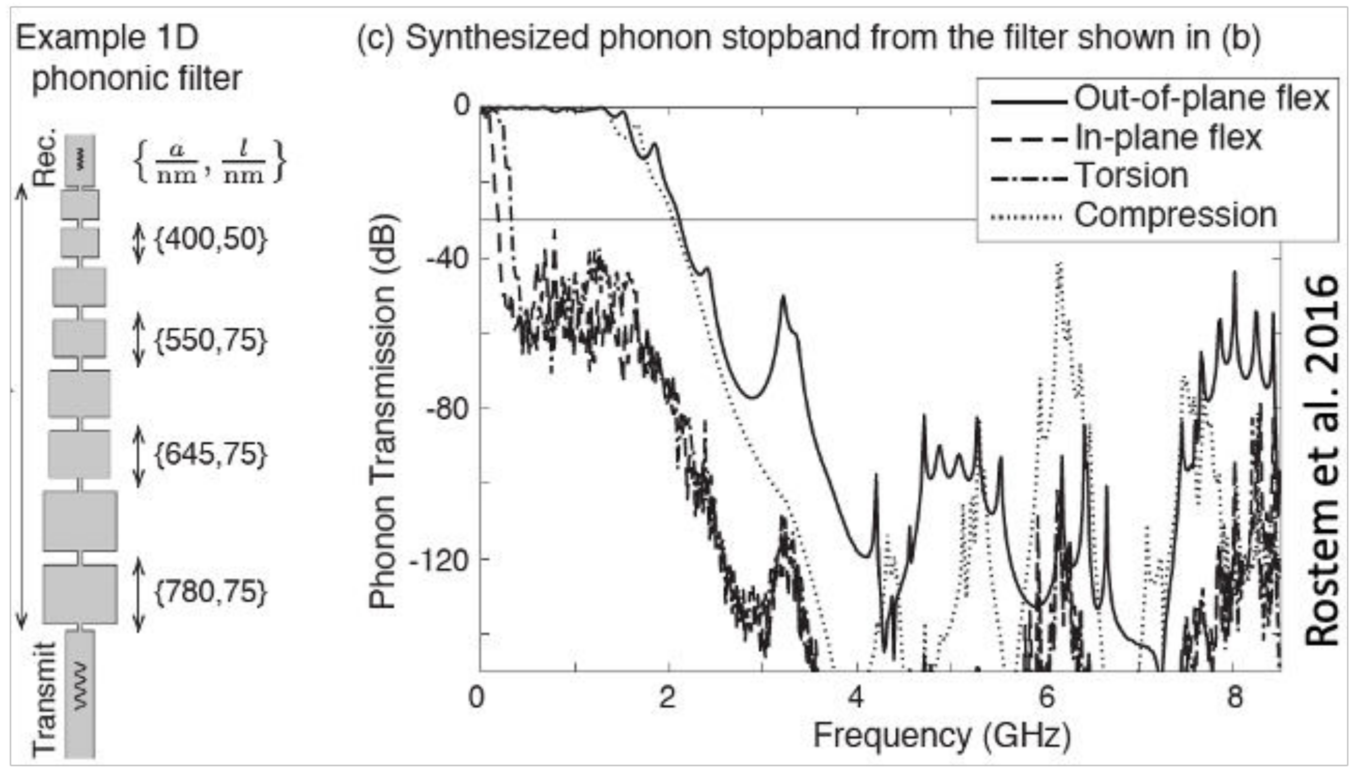
ASTHROS will also demonstrate key technology and science applications necessary for future NASA space missions



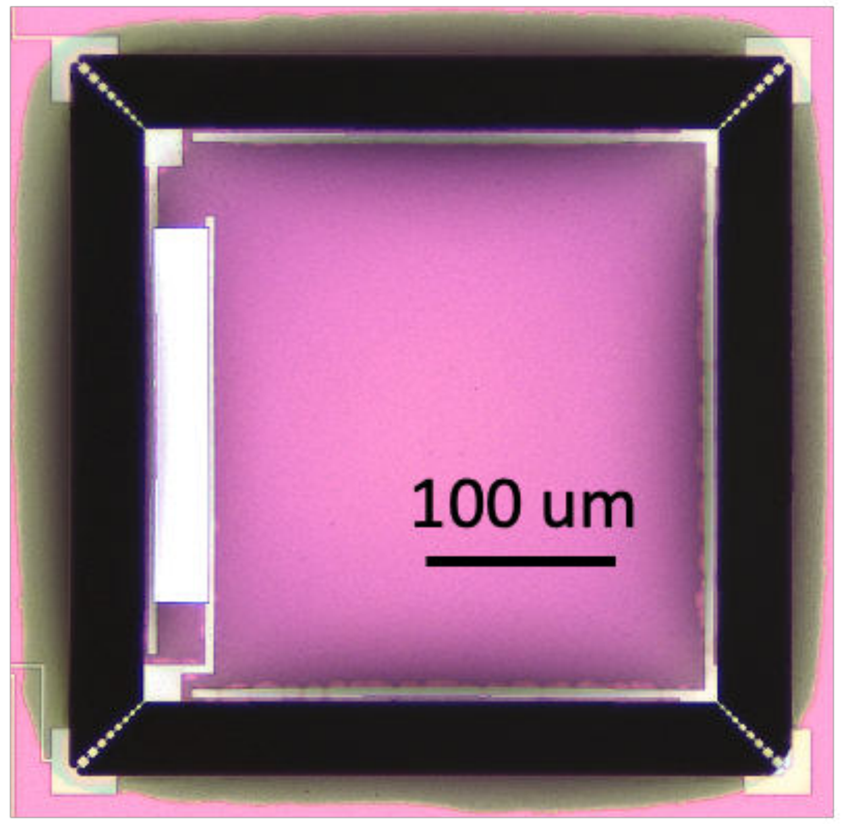
Courtesy J. Pineda

Photonically-isolated TES Bolometers

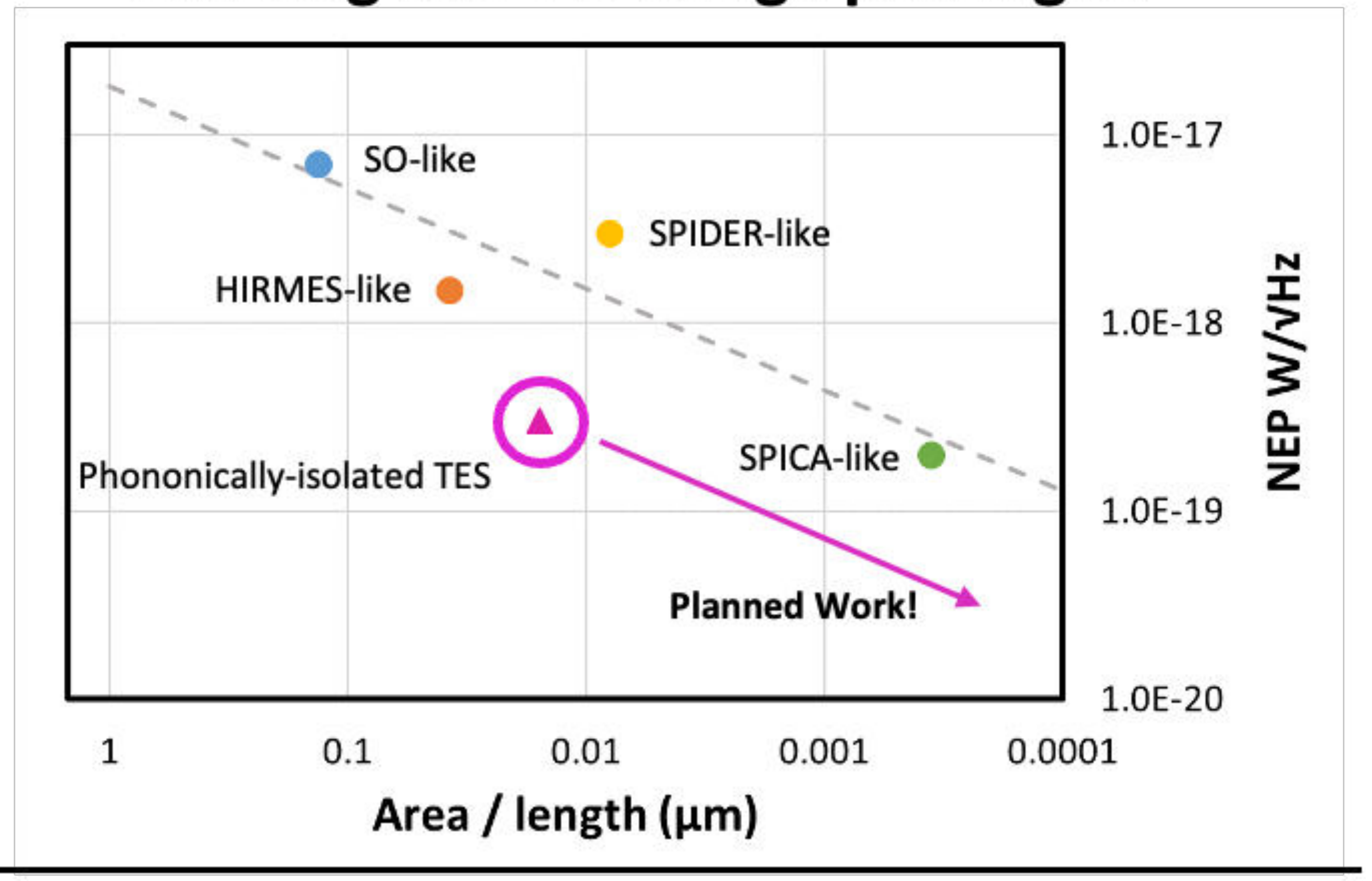
Tailoring Phonon Transport – A Path to < 1x10^{-20} W/√Hz



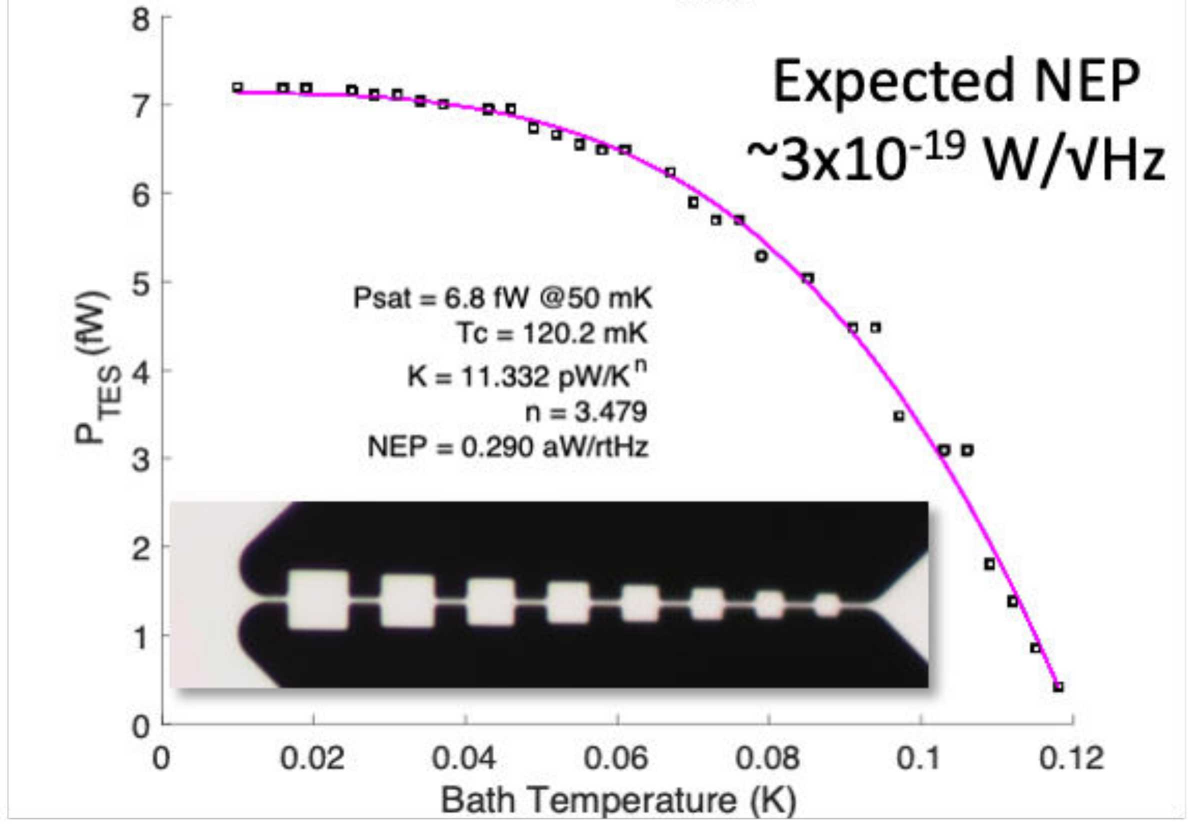
Fabricated Pixel



Breaking the TES design paradigm!



Measured P_{Sat} Curve



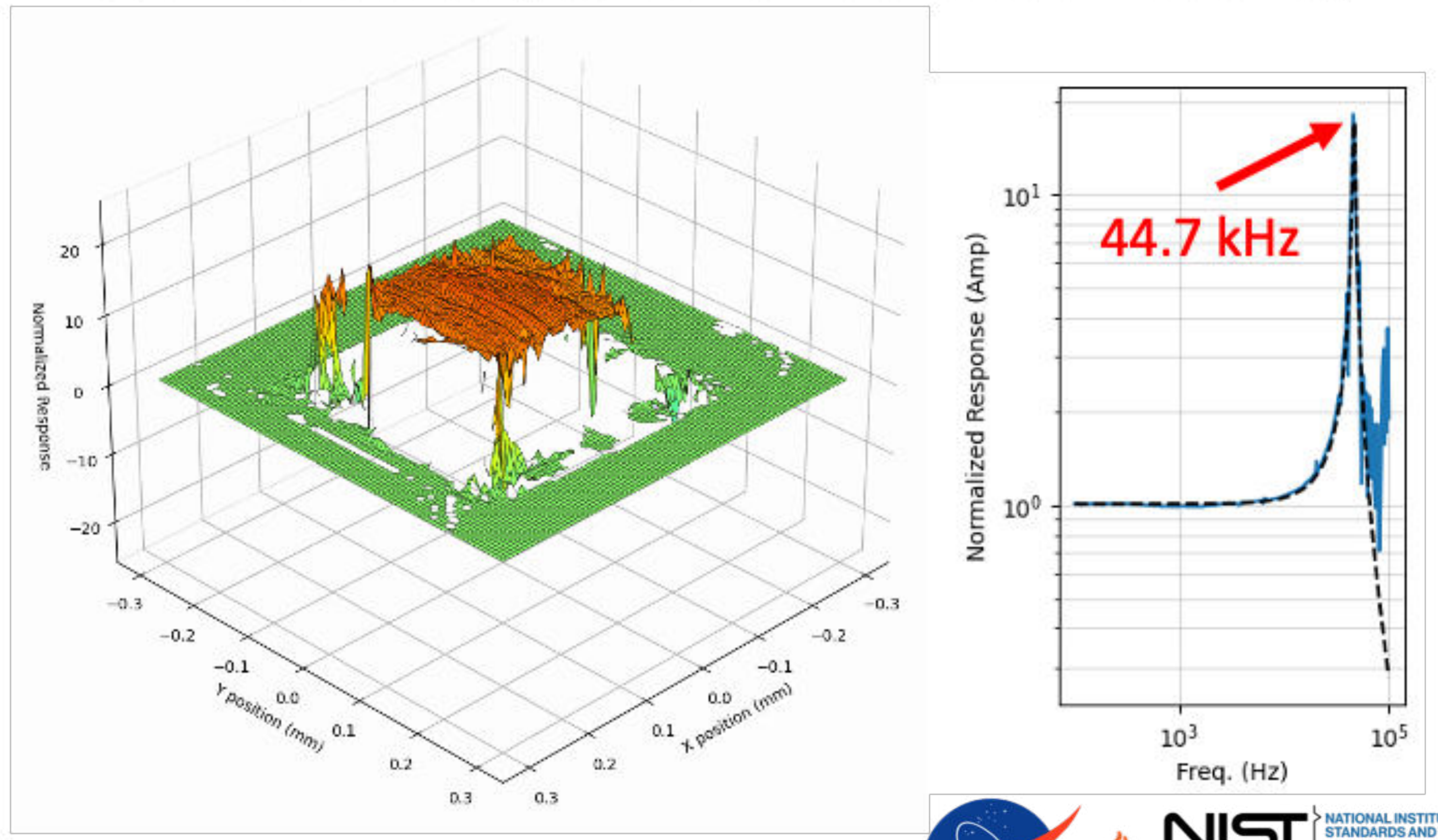
Phonon engineering **can** be used to define G with TES leg geometry, allowing us to break from diffusive transport design curve

Prototype devices have demo'ed Psat consistent with ~ 3x10^{-19} W/√Hz

Future work will push leg geometry to finer features to further reduce G

Laser vibrometry indicates likely survivability during rocket launch

Laser Vibrometry to demo Launch Survivability

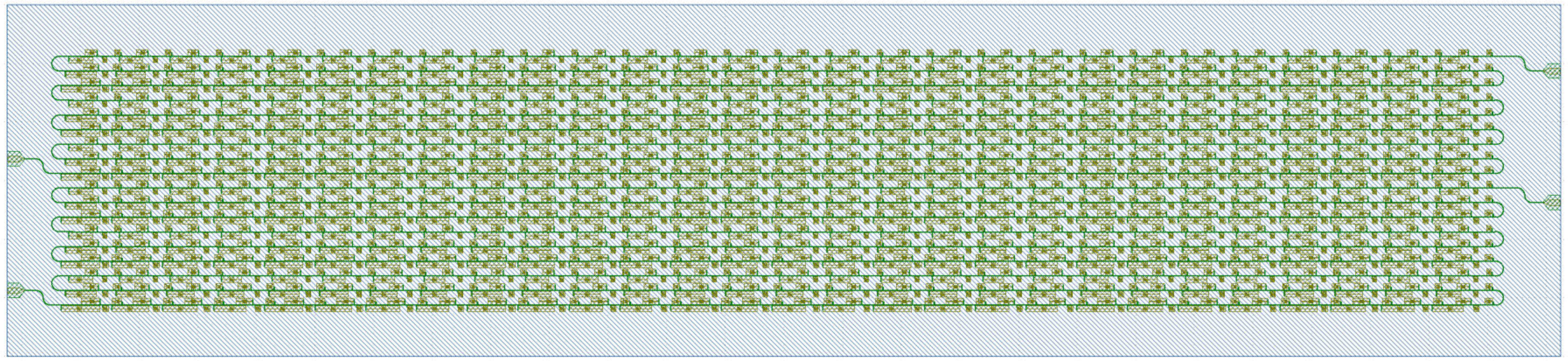


Courtesy J. Connors, K. Rostem

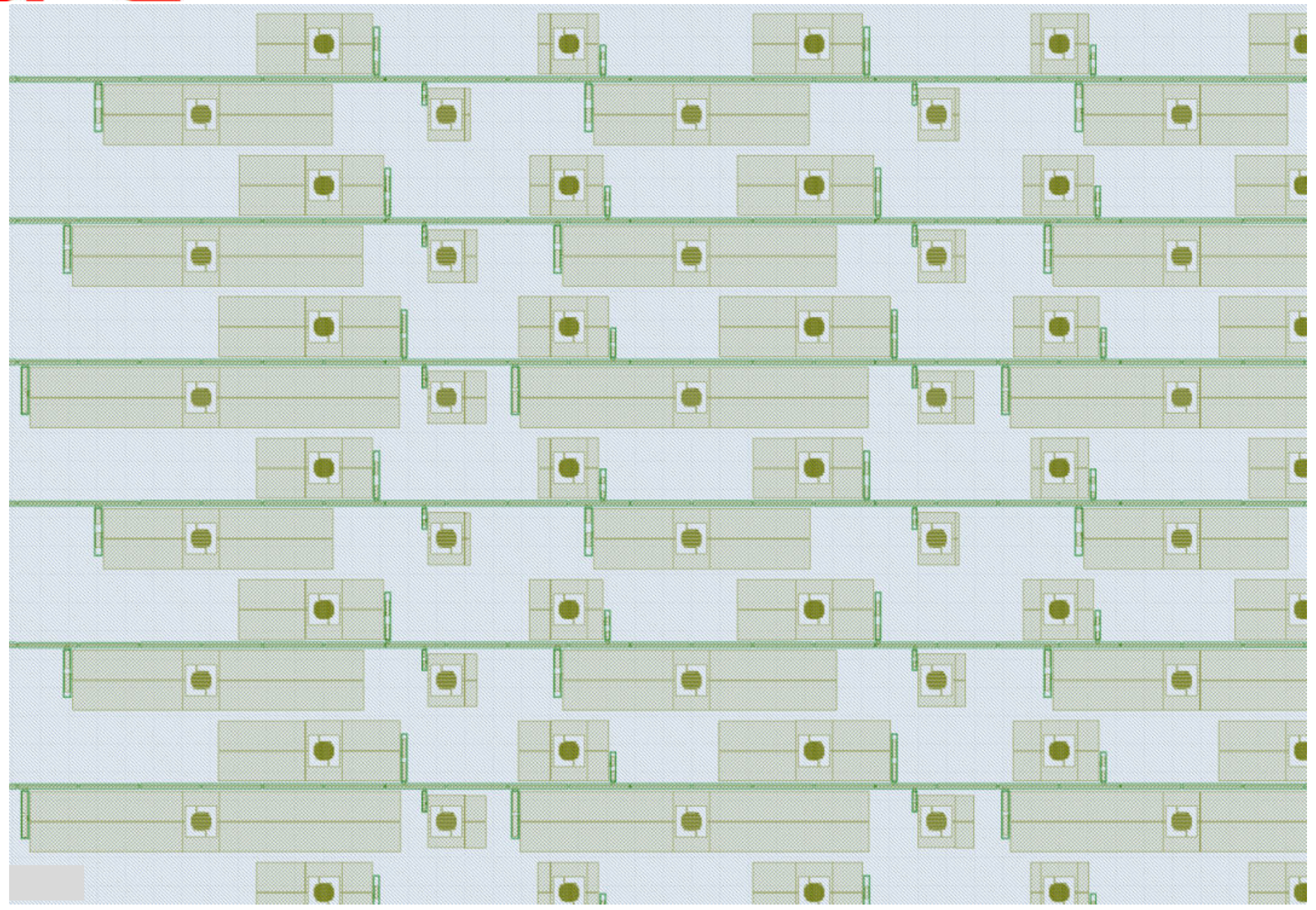
Low Noise MKIDs

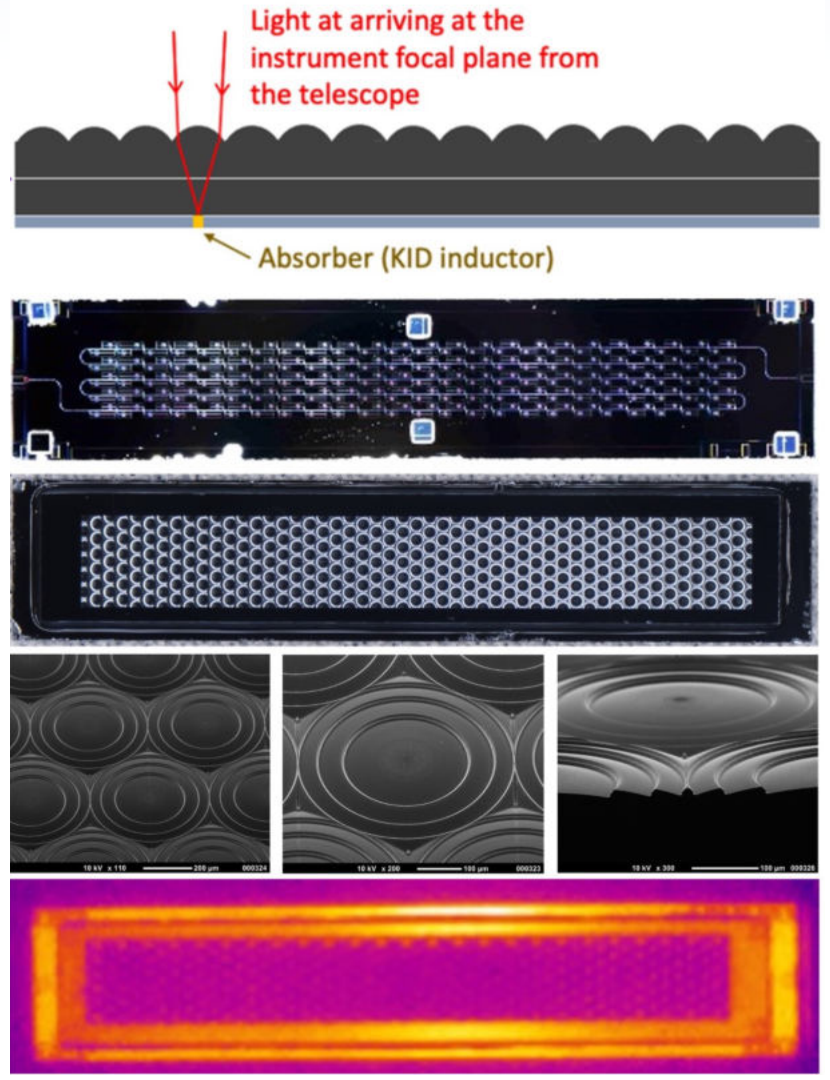
PRIMA The PRobe far-Infrared Mission for Astrophysics

Kinetic Inductance Detectors – the miracle making this possible!

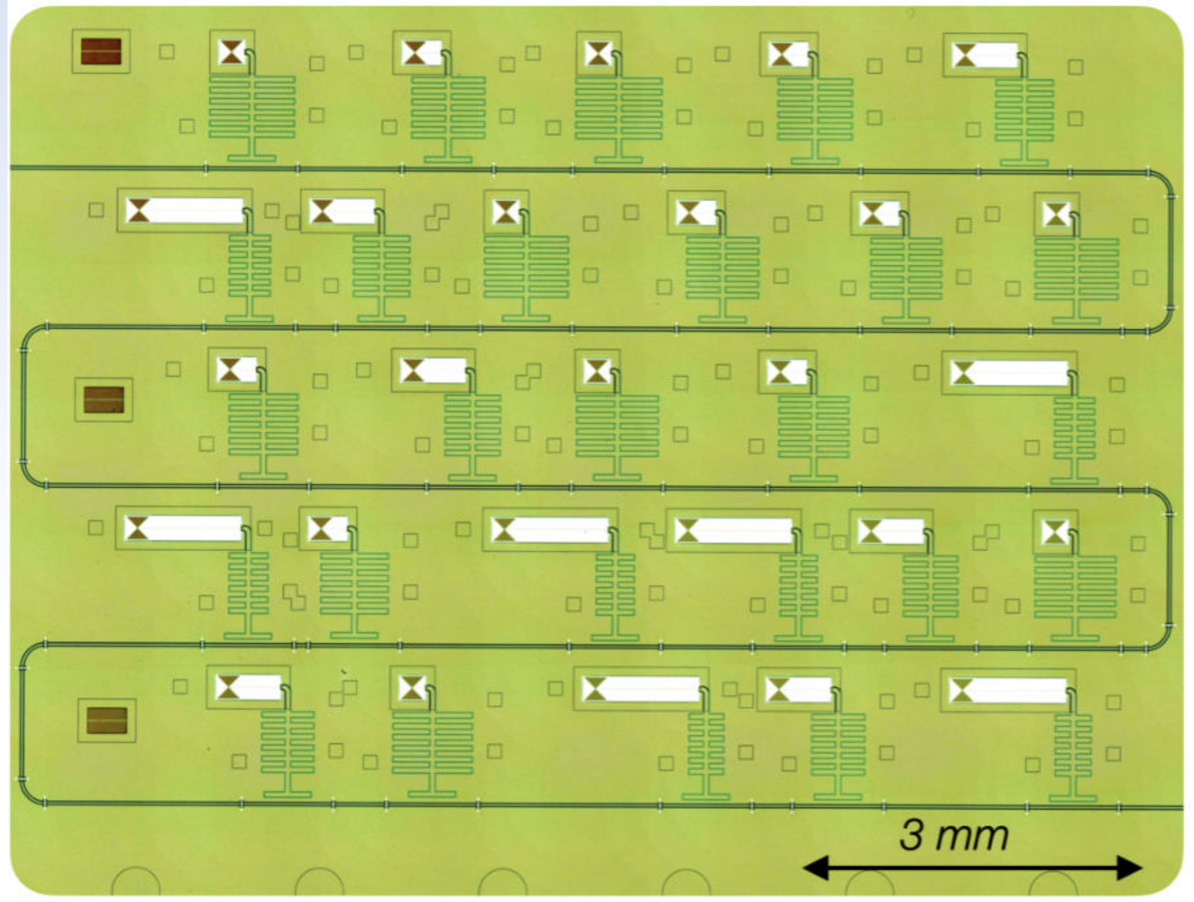


JPL 1000-pixel PRIMA subarray at JPL, >90% yield already





GSFC etched micro-lens arrays interface with JPL KIDs.



SRON Netherlands Institute for Space Research

World's most sensitive KIDs from SRON.

Collaboration bringing JPL, SRON, and GSFC together to deliver this exciting and crucial enabling technology.

Courtesy M. Bradford

Strategies

What Should We Be Thinking About?

- **Advocacy for opportunities.**
  - Access to space is critical for FIR.
  - APEX-class mission, yes, but increased access to balloons and other sub-orbital payloads.
  - Community access to ground-based assets for both development and science.
- **Training the next generation of scientists.**
  - Need to retain knowledge and capability. This requires investment - and opportunities to practice!
  - Applying new techniques and physics (eg meta materials, cryogenics, etc). Commercialization?
  - Attracting the best young talent to develop workforce for the future.
- **Playing the long game.**
  - Opportunities will remain rare and hard-won. Support relevant APRA, SAT, and ATI programs as much as possible.
  - Advocacy for our science and how its insights are unique as and where possible.

Thanks!

Backup Slides

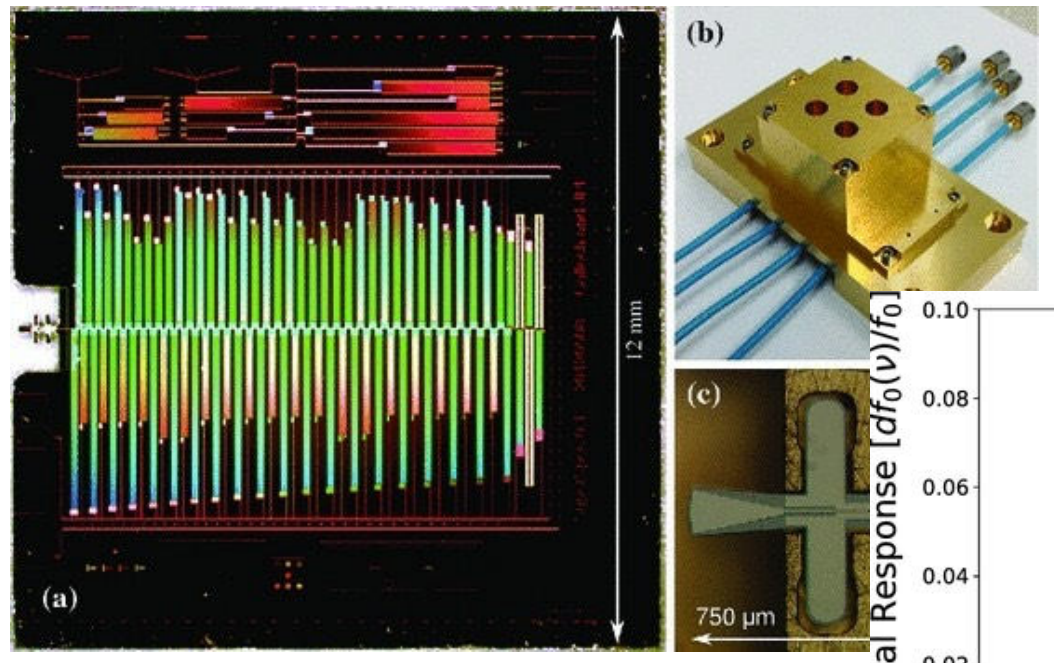
Technologies to Watch

What's Coming Down the Pipe?

What About Interferometry?

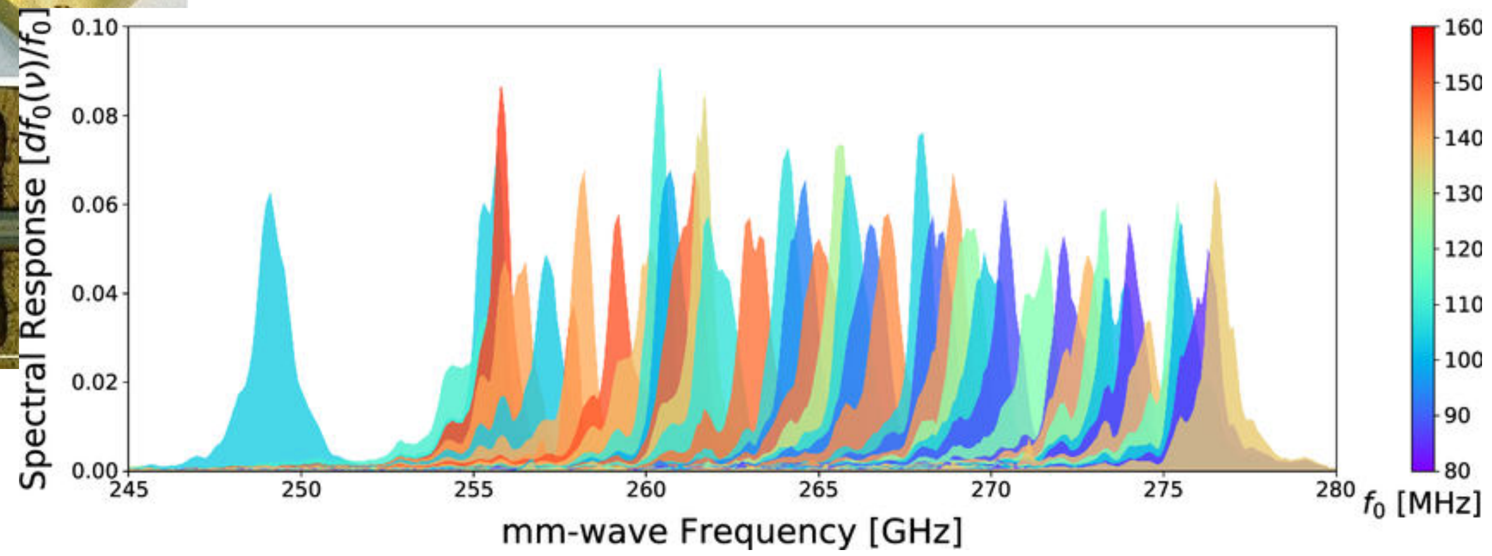
Yes! But: nothing is free, this would trade things like mapping speed and free spectral range against angular resolution and spectral resolution.

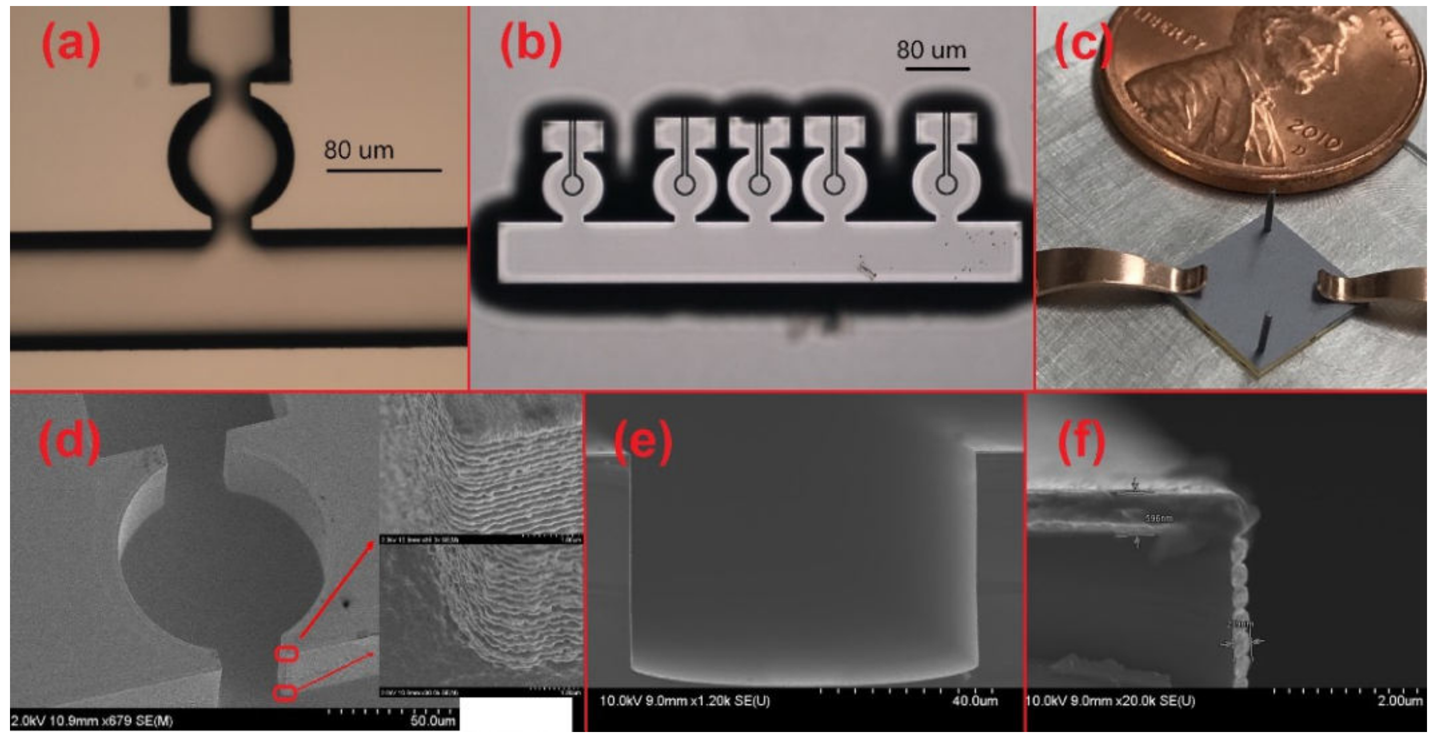
Quasi-photonic Approaches

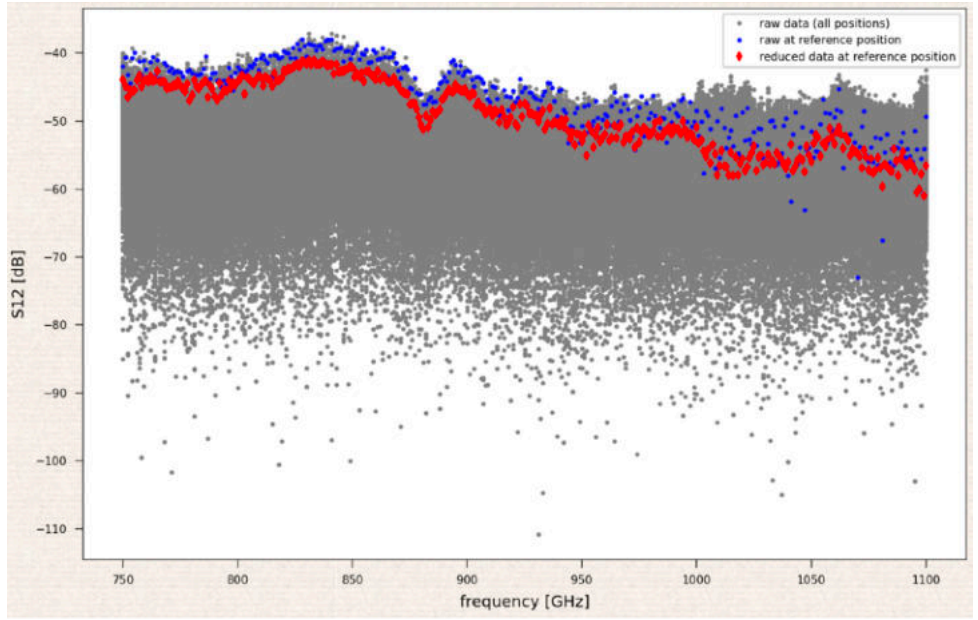


SuperSpec (Shirokoff et al)

On-Chip dispersion offers a lot of SWAP advantage.



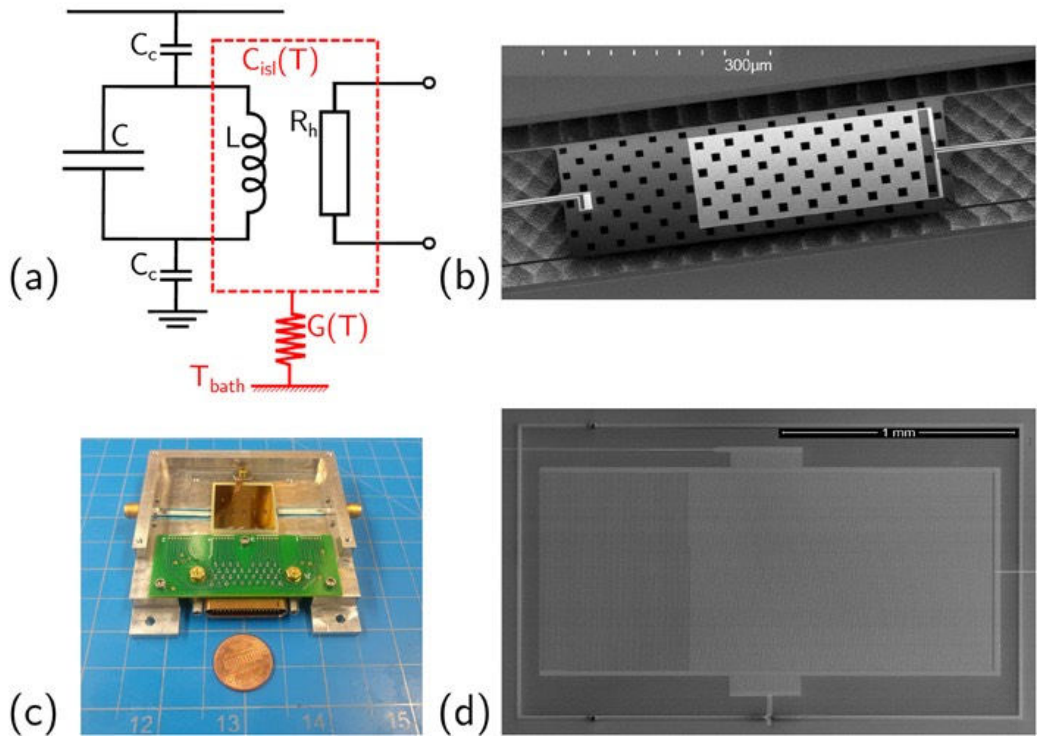




THEMIS Collaboration (Gradziel et al)

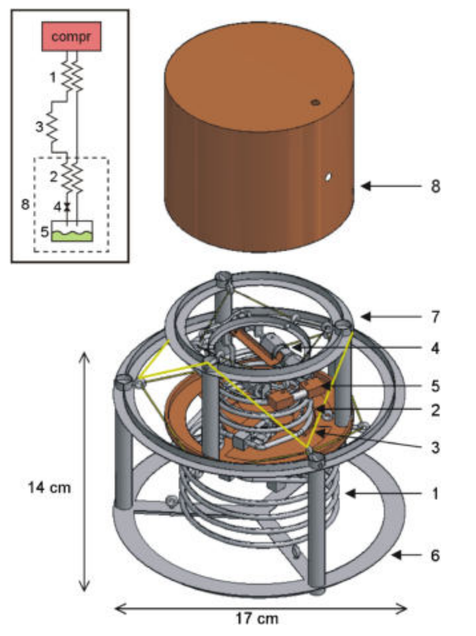
Detectors

- Alternative technologies like high-frequency TES detectors or Thermal KIDs (TKIDs) may offer advantages.
- We should keep our minds (and wallets) open.

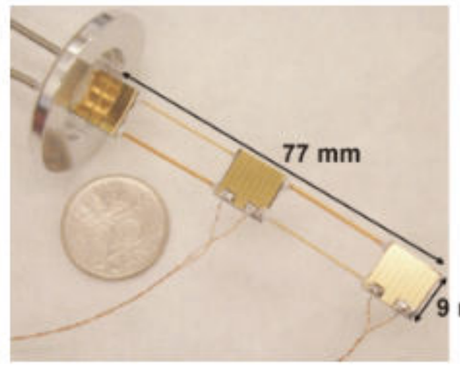


Miniature Cryocoolers

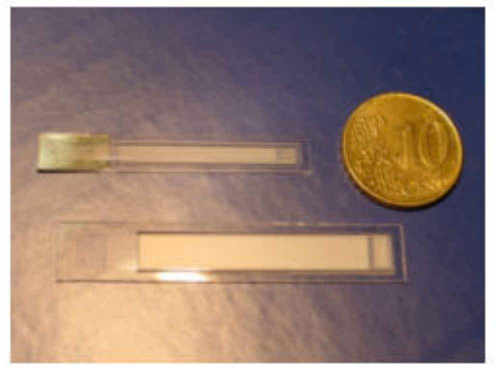
- Many interesting miniaturized approaches, including miniature sorption coolers (left) and miniature JT-coolers (right).
- Could use investment.



Burger, ter Brake, et al. (2007)



First MEMS-cooler of Burger et al.



Lerou et al. (2006)